Future studies
on the energy transition

Technical file #1 – Draft version

Information and recommendations for scenario producers

This document is part of a set of 12 technical files. These files have been produced by *The Shift Project* after one year and a half of research and experts consultations on the different aspects of energy transition and the future studies around these aspects.

Our project, "Power Systems 2050 – Guidelines for design," started in January 2018, with the participation of 10 experts who defined the key subjects which according to them have to be collectively tackled by future studies about the power transition. *The Shift Project* then investigated each of these subjects, consulting in total 40 experts, organizing 4 workshops, and reviewing a large bibliography, including a dozen of future studies about power (and energy) transition at different geographical scales.

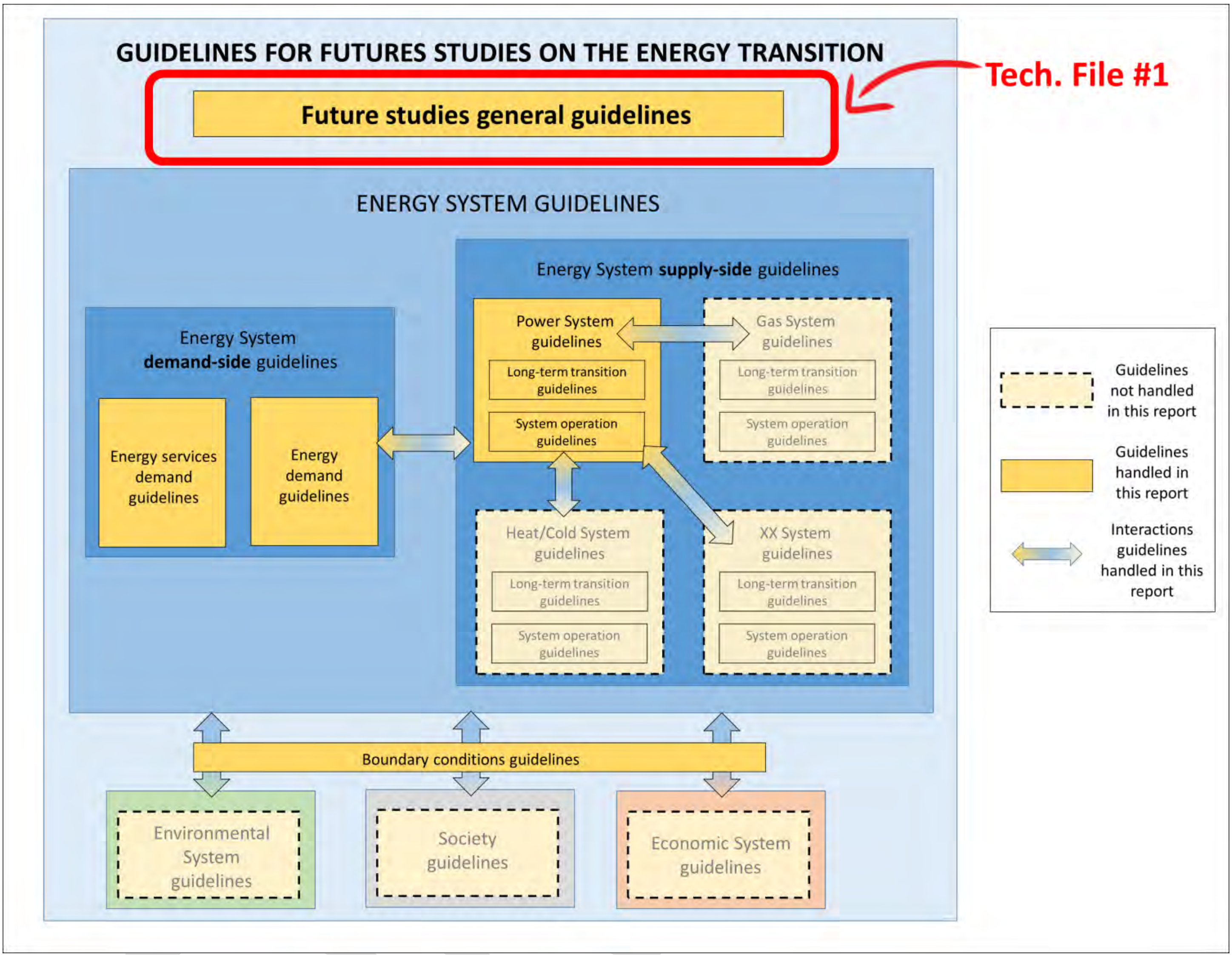
The goal of this project is to produce a set of guidelines addressed to scenario producers. These guidelines seek to foster transparency and consistency *within* future studies and to develop a common language *across* studies. By defining a number of important items which are key to deal with in future studies, we actually propose a study template which enables a better understanding of the location of each proposed scenario on the tree of possible transitions. Once again, the objective is not to *rank* studies, or scenarios, but rather to *compare* them to get a better collective overview of the different aspects of the transition (what are the differences between studies in terms of driving questions, hypotheses, models, methodology, results?).

Several aspects of the energy transition are handled in these technical files. However, on the energy supply-side only the power system has been studied. The main reason for this choice is that we had to start from somewhere with limited resources, and the power system seemed to be a key system to study in the energy transition context, towards a low-carbon economy, as shown by the growing number of future studies focusing on this system. However, the guidelines we propose could be completed by analyzes on the other energy supply-side systems (the gas system, oil system, heat system and so on).

Each technical file tackles several aspects of future studies for the power (and energy) transition. Here is the complete list of the technical files produced during the project:

#	Technical file title
1	Future studies on the energy transition
2	Energy transition models
3	Boundary conditions for energy transition scenarios
4	Long-term evolution of energy consumption in energy transition scenarios
5	Lifestyles and consumption behaviors in energy transition scenarios
6	Long-term evolution of the power system supply-side in energy transition scenarios
7	Power system operation in energy transition scenarios
8	Impact assessment in energy transition scenarios
9	Transition desirability in energy transition scenarios
10	Environmental assessment of energy transition scenarios
11	Economic evaluation of energy transition scenarios
12	Employment assessment of energy transition scenarios

Altogether, these files cover the fields described on the following map of the guidelines for future studies on the energy transition. The document you are reading covers the red-circled topics.



In addition to these technical files, three complementary notes have been produced as specific focuses on the following aspects: material criticality in energy transitions (in French, to be translated and added to technical file #10), levelized cost of electricity (LCOE) in energy transition future studies (in French) and discount rate in energy transition future studies (in French).

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Table of content

Reading keys

Explanation box, containing key information for a better overall understanding of the subjects.

Recommendations for scenario producers:

These boxes contain the recommendations for scenario producers.

The word "should" means that scenario producers, if they are to follow the guidelines, must substantiate the corresponding point. The words "may" or "might" relates to suggestions, ideas to help the scenario producer respond to the point.

Questions in italic are examples of questions scenario producers might ask to substantiate the points. They are here in an illustration purpose.

Phrases in italic in the text are words which are being defined and will be subsequently used in the framework.

Phrases which are highlighted in yellow refer to other technical documents of this series.

I. Future studies should work together to better achieve their common goals: informing and influencing

A. Future studies are a way to answer questions about the evolution of complex and uncertain systems, such as the energy system

According to (Guivarch, Lempert, & Trutnevyte, 2017), "[w]hile no universal definition exists, scenarios have been described as plausible descriptions of how the future may develop, based on a coherent and internally consistent set of assumptions about key relationships and driving forces."

The scenario approach arose when the questions at stake dealt with highly uncertain and complex systems. Complexity characterizes interconnected systems, with feedback loops and non-linearities, in which interesting outcomes are diverse in nature and in which processes are cross-scale. Uncertainty characterizes the inability of experts to agree on models that link drivers shaping the future, on the parameters in these models and/or in the value of outcomes (Guivarch et al., 2017).

Future studies use scenarios as tools to answer questions about the future

A *future study* aims at answering one or several questions (the *driving questions*) about how the future may develop, by bringing into play one or several *scenarios* which are compared together.

Given the deep uncertainty of long-term future developments, scenarios are *not* predictions and should not be considered as such (IDDRI, 2013).

B. Future studies aim at informing and influencing a target debate

The ultimate goal of a future study is to change the behaviors, ideas, or speech about a given debate, of those who get in touch with it (either directly, or through other media), ideally the target audience. Firstly, the future study must be read, or listened to, by the target audience. And then, readers might change their behaviors and ideas after their contact with the study. Depending on the study's target audience, the following changes may happen:

- The study has a policy decision-making support function: Political decision-makers may take a different decision or change their speech because of a study.
- The study has a mass communication function: Citizens (as consumers or voters for example) can change their individual behaviors or speeches.
- The study has a business decision-making support function: Companies may adapt their strategies or communications after reading a future study.
- The study has a research function: The scenario community (see section on scenario community) may ask questions about, and discuss, the study, its hypotheses, model and results. It can also launch new studies.

A future study is usually communicated through a report which can come along with a website, interactive data, open sets of data, infographics, videos, etc. Study reports usually contain the description of several scenarios as well as information about how they were designed, about the models used to build them consistently, interpretations of their results, and comparisons between them. Finally, the report answers the driving questions and takes an oriented glance depending on the target-audience and the decision-making processes it seeks to influence. In this respect, the report might link the results to recommendations towards the target audience and develop a specific storytelling to make sense of the results toward action. After publication, the study is usually promoted through conferences, meetings, etc.

Hence a future study aims at informing *and* influencing. Due to their forward looking nature and their object (the evolution of human systems), future studies included in our scope are political objects per se.

C. Our scope: future studies dealing with power systems and addressed to policy makers and the greater public

In this document, we only consider studies about energy systems evolutions. Our guidelines will more particularly target the descriptions of the evolution of the power systems in studies including this sector, but not necessarily limited to it: some studies explicitly focus on the power sector while some others study the whole energy sector, or even the whole economy. Studies usually investigate interactions between the systems they consider, e.g. CO_2 emissions, which is an interaction between the energy system and the atmosphere. Hence our scope includes the description of the power system as well as all the interactions it has with other energy sub-systems and surrounding systems (see Figure 1).

Scenarios produced by strategy departments of companies and used as internal tools for strategic planning are outside of our scope. Included in our scope are reports and papers which are published and which can be debated about by policy-makers, citizens and the scenario community (see section on scenario community).

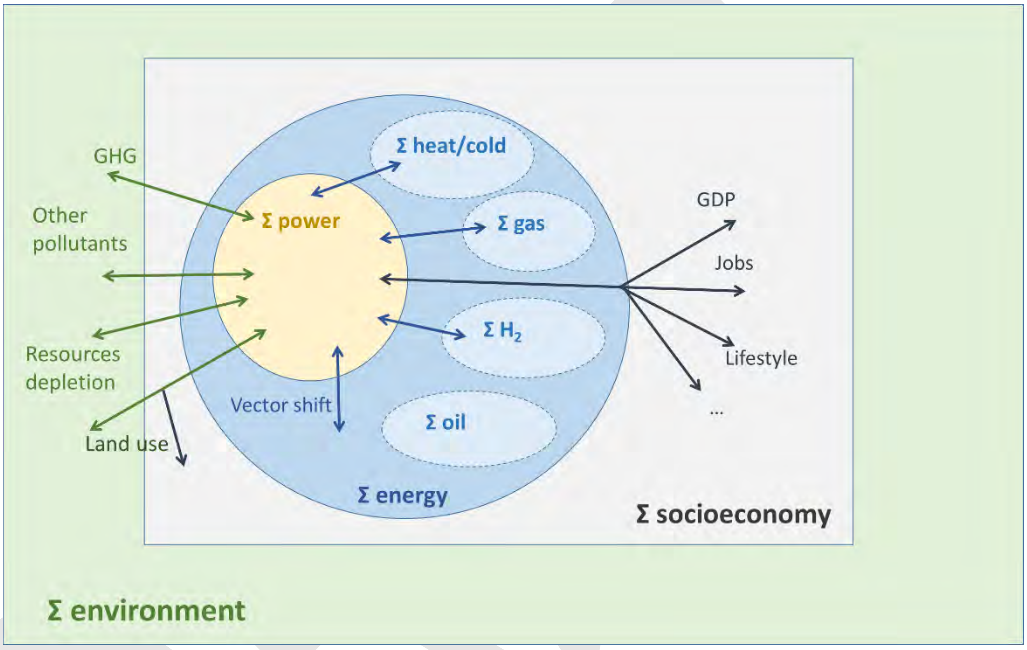

Figure 1: The environment is the ground for human societies to live, produce, transport, exchange and consume goods and services (which is called the socioeconomic system here). A part of the socioeconomic system is the energy system, in which energy is produced, transported, exchanged and consumed. The energy system is itself composed of several sub-systems, such as the oil system or the power system. These subsystems interact with each other (double arrows). The "Σ" symbol means "system" in this diagram.

D. Producing a future study is a complex work involving several actors

Future study activities are composed of a series of different activities (see Figure 2). These activities are described here as being separate and sequential for the sake of simplicity. In reality, some activities are performed in parallel or back and forth via mutual feedback.

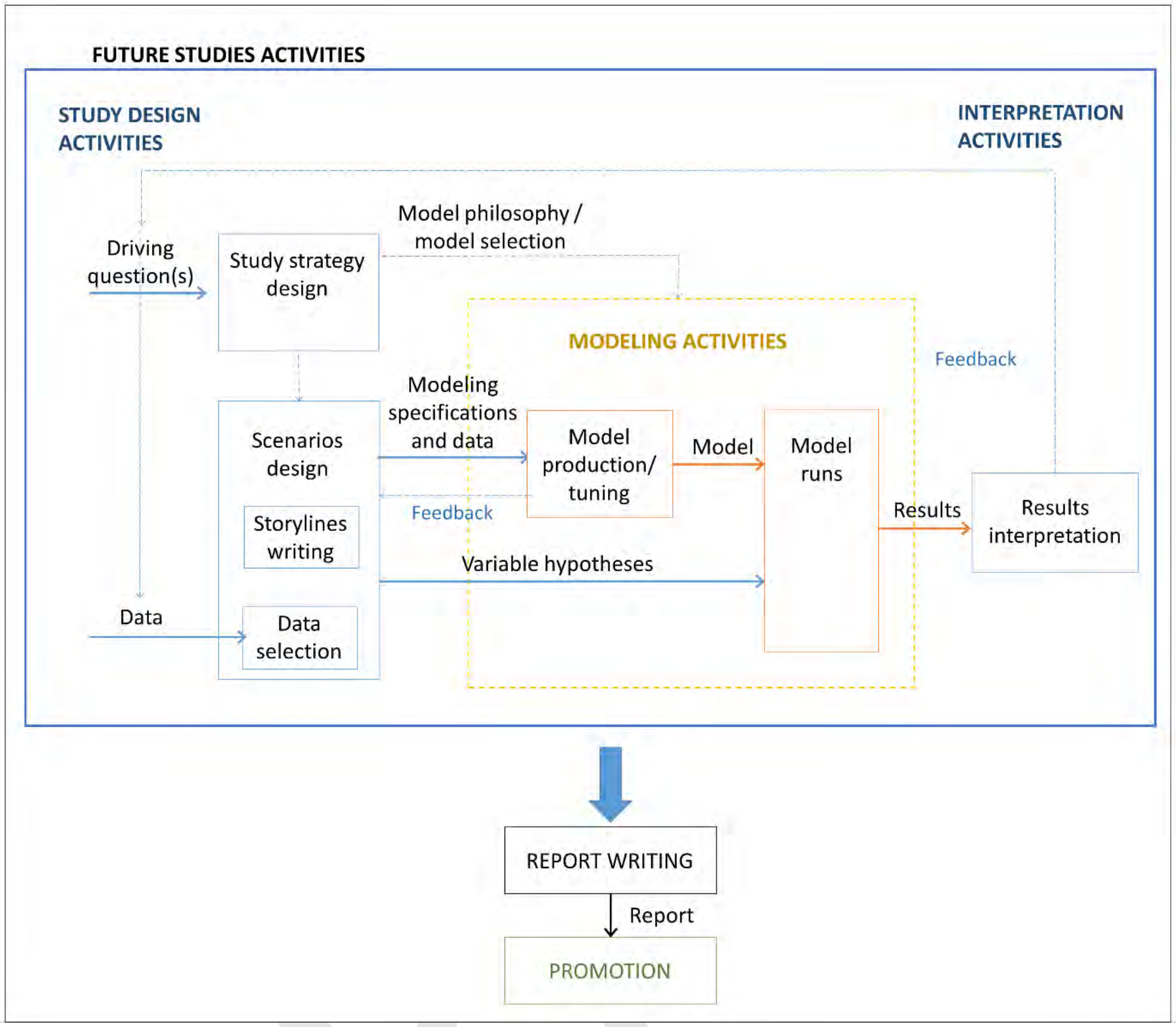

Figure 2: The different steps of future studies production, from study design activities to promotion.

A set of driving questions is at the origin of the future studies activities. Scenario producers start by designing a study strategy in which they define the main characteristics of their study, such as its scope, the different scenarios that they will bring into play and the parameters they will compare, as well as the type of models they will use to compute results.

Then they design more precisely the different scenarios of their study. They detail the individual story that each scenario will tell, and how it differs from the other stories. Also, they select the databases that will feed into their model(s). Scenario producers might invite experts or stakeholders to participate in the study strategy design, the scenarios designs and data selection and validation.

A model may have to be designed and implemented for the study (model production), or may already be available from previous studies or from specialized companies. Either way, the model may have to be tuned to fit the different storylines of each scenario. Sometimes, data pre- or post-processing modules are implemented. Pre-processing modules enable the selected data to be used as inputs of the main model. Post-processing modules enable the proper interpretation of data and their proper final publication.

Once the model is produced, or properly tuned, the different scenarios can be computed (model runs). The runs provide the raw data which are interpreted by scenario producers.

Often, scenario producers discover interesting results which trigger new driving questions, or alter the original ones. Also, they might want to choose new input data after considering their results.

Once satisfying results are obtained, a report about all the activities is written, published, and is generally promoted.

Studies are the result of several activities, in some cases performed by different actors. Some associations or NGOs[1], think tanks[2], foundations[3], public agencies[4], companies[5] or individuals engage in future studies activities and/or modeling works. Some companies[6] or research laboratories[7] are specialized in modeling and data selection and also develop skills in scenario production.

The first set of actors is called in this document *scenario producers*, while the second group is called *modelers*.

Finally, some companies and institutions[8] publicly provide, or sell data about the current state of the world.

E. How to make studies work together even if they do not answer the same questions?

Different studies generally ask different driving questions. Thus it is rarely relevant to ask "which study is right or wrong". Each study aims at informing about specific aspects of the energy transition, which might not be the aspects that other studies handle.

Hence it is by nature not relevant to compare the results of studies between them: why comparing the answers if the questions are not the same? (Hache & Palle, 2019)

Everything comes from the driving question

The driving questions drive the whole scenario work. They are chosen by the scenario producer depending on their target audience, or the decision making process they seek to influence, and the message they want to convey.

Is the study addressed to political decision makers? To the greater public?

Do the study producers want to describe a desirable world and show how it could be reached? Do they want to show how a particular set of technologies (for example linked to a particular energy vector, or a particular power production technology) fits in a variety of future worlds? Do they want to study the viability of a disruptive energy system structure? Do they want to suggest policies to implement?

The answers to these questions lead to the driving questions.

Here are examples of driving questions:

1 - What would be the implications of reaching a fourfold decrease of CO_2 emissions in France by 2050 through energy sobriety, energy efficiency and an energy supply portfolio of low carbon technologies, for the environment, the economy, lifestyles, research activities and energy industry activities?[9]

2 - What impacts of measures favoring energy efficiency, renewables, nuclear, or Carbon Capture and Storage (CCS) in EU by 2050 on energy consumption, the energy system, security of supply, CO_2 emissions, and expenditures for households and industries?[10]

3 - Is it technically and economically feasible to achieve at least an 80% reduction in greenhouse gas (GHG) emissions below 1990 levels by 2050, while maintaining or improving today's levels of electricity supply reliability, energy security, economic growth and prosperity in EU?[11]

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[1] Negawatt, Sauvons le climat, Réseau Action Climat – France, WWF, Greenpeace…
[2] The Shift Project, Agora Energiewende…
[3] European Climate Foundation…
[4] ADEME, European commission…
[5] EDF, RTE…
[6] Enerdata, Artelys E3-Modelling,…
[7] Centre de mathématiques appliquées (CMA) at Mines ParisTech, Laboratoire d'économie appliquée à Grenoble (GAEL), Joint Research Center (JRC)…
[8] Enerdata, IEA, The World Bank, OECD, GaBi…
[9] This question could be the driving question of (ANCRE, 2013)
[10] This question could be the driving question of (European Commission, 2011)
[11] This question is the driving question of (ECF, 2010): p6.

Questions 1 and 3 are about a desirable world to reach by 2050 (low carbon emissions) whereas question 2 is about exploring consequences of different policies. The three questions might lead to formulate policy recommendations, but only question 2 phrases it explicitly.

The driving questions, even though they might be an efficient introduction to a study, do not tell everything: for example, the main assumptions and the model philosophy are not mentioned.

Questions can be quite various and can reflect different objectives: some will question the possibility to reach desirable targets or to follow a desirable vision about the transition and reveal the barriers and challenges to overcome; some will question the least regret actions[12], or try to reveal the consequences of following different pathways along selected dimensions (for example, GHG emissions, or unemployment, etc).

However, even if studies answer different questions, they should as a whole bring more information than taken separately, by informing different aspects of the energy transition. Studies could be seen as a cooperative way to inform the possible energy transitions. Developed in a proper way, the more studies, the more knowledge about the consequences of taking different transition pathways, hence the more informed and democratic the debate about the energy transition.

Recommendations on study drivers

The driving questions of the study should be explicitly stated (Cao, Cebulla, Gómez Vilchez, Mousavi, & Prehofer, 2016). The following elements may be included in the driving questions:

- Scope elements: the end date of the study, its geographical perimeter, the covered sectors and the main parameters which are under study (such as CO_2 emissions, electricity security of supply, lifestyles, agents expenditures, etc).
- Social objectives elements: if a desirable world is to be reached, the main dimensions of this world should be mentioned (such as the level of CO_2 emissions, the level of power security of supply, etc).

The scenario producer should explain the context within which the driving questions were asked so as the reader understands why other possible questions were not asked. The following aspects can be developed:

- The target audience of the study. *Is the study mainly addressed to a specific audience? What audience?*
- The decision process the study seeks to influence. *Is the study specifically tailored to inform a particular decision-making process?*
- The novel information brought by the study. *What is different from the current state of research?*
- The way the study should inform and or influence the target audience or decision process. *For example, a study might want to inform decision makers about the risks posed by nuclear power and climate change, and influence them towards measures for consumption reduction. Or, a study might want to inform about the positive role that nuclear power could play in terms of CO2 emissions reduction at low cost and influence decision makers towards measures favoring nuclear power development. Etc.*

F. Our goal: uncovering the map of the possible energy transitions…

The possible energy transitions (the ones that "succeed" as well as the ones that "fail") could be seen as a *transition map* which has to be uncovered as most as possible before choosing which way to go. Each point on the map would represent a future world and the transition to reach it. Uncovering the map would then be equivalent to knowing the world where we choose to head to and the consequences of transitioning to that world.

[12] The actions which can be undertaken on a short-term basis without significantly impairing any desirable scenario to happen

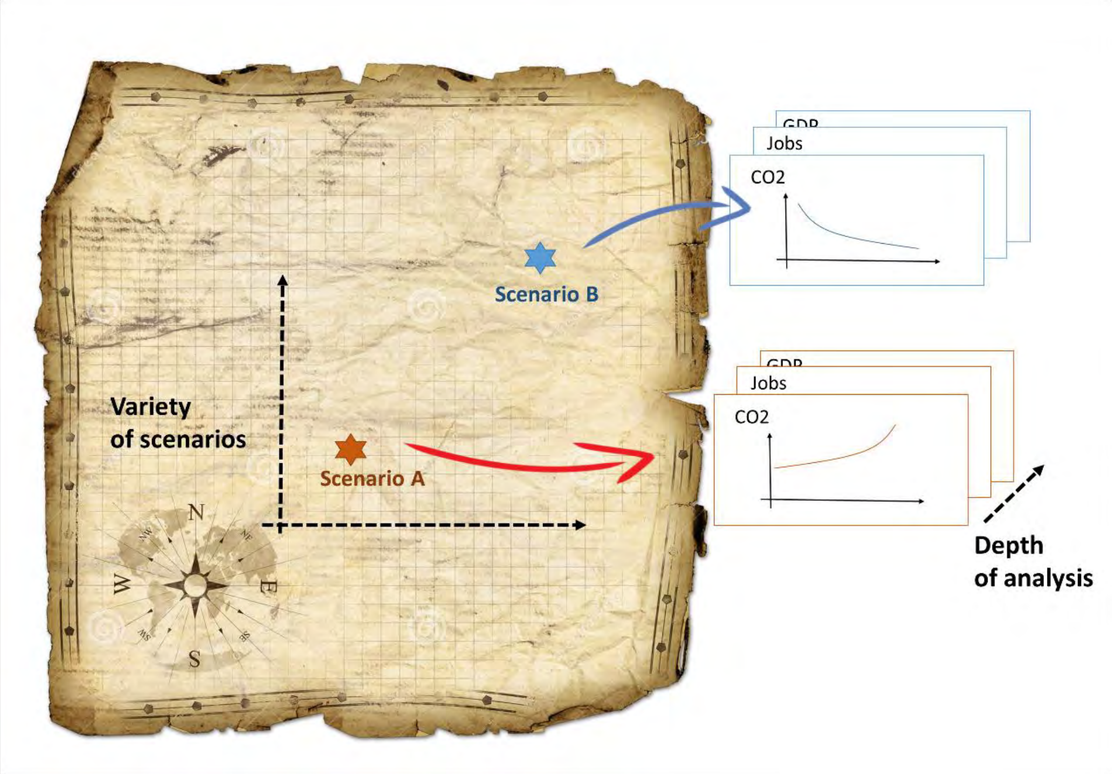

Figure 3: The transition map indicates the different worlds we can decide to head to. The role of future studies is to uncover as most as possible the transition map, in terms of scenarios diversity and depth of analysis (diversity of considered variables). Source: The Shift Project. Image: dreamstime.com

The present methodological framework aims at creating a common and shared frame for future studies productions, enabling them all to participate in the same debate and to bring their ideas and knowledge in a constructive way. This would place them on the same transition map and help the reader quickly uncover the parts of the map that the different future studies inform.

This framework deals with energy system transition scenarios. The energy system is in majority a physical system[13] and as such it follows the laws of physics, most of them being well known by physical science. Our framework takes as granted that any scenario should respect the laws of physics if it seeks to seriously inform the energy transition debate – an important enough topic to be extremely seriously informed and thought of.

G. **...And** reinforce and connect existing scenario communities

The scenario stakeholders are scenario producers, modelers, users of scenarios (policy makers), and experts from various entities (companies, university, NGO's, think tanks…), or citizens, who participate in the design of future studies.

Scenario stakeholders seek to inform and influence the energy transition debate. They form teams for producing specific future studies, or they gather and share information around specific models[14]. They occasionally gather for events to share modeling practices[15]. However, the different teams and projects do not collectively coordinate in their effort to inform the energy transition debate, which is the reason why we decided to build the present methodological framework.

[13] It is partly a human system though, through decisions related to consumption
[14] Such as IEA-ETSAP community sharing data and good practices around the TIMES model
[15] Such as events organized by the Energy Modeling Forum by Stanford University

For the time being, at national level scenario teams gather for some special occasions, such as particular political processes[16]. At EU level, efforts linked to the Energy Union framework, by ENTSO-E (through the TYNDP package) or the Joint Research Center (JRC) are being made to reinforce the scenario community.

A grown-up community would share data bases, comment on them, improve them. Similarly, they would discuss, share and improve energy system models. Community is even considered by researchers as one of the most efficient ways to grasp complexity (Hache & Palle, 2018). Studies could partly become collaborative. For example, a team specialized in the impact on material resources could assess the consumption of other scenarios, in a partnership.

However, the emergence of such a community needs a fertile ground fostering trust within the community: transparency of data and models as well as transparency in the interests of each member of the community are the key components of this ground.

1. Transparency is key for a healthy energy transition debate

Transparency pertains to the providing of data, but also to the way these data are provided. Too much data, or poorly organized data does not improve transparency. Transparency is about providing digestible intelligence. However digestibility depends on the target audience: scenario producers should be transparent towards the greater public (including policy makers) and towards the scenario community (experts).

As a result, two levels of transparency should be targeted. Report publication, for the greater public and policy makers, is the first level. Deeper data publication is the second level. This level is extremely important for the sustained good health of scenario community and, with it, the health of the energy transition debate.

For example, JRC projects should target the second level of data publication (some exceptions apply though, such as the respect of the privacy and integrity of the individual or the respect of commercial interests or intellectual property of legal entities) (Joint Research Center, 2015).

a. Our framework fosters data transparency towards policy-makers and the greater public

Future studies publish data in their reports, through publishing their results and through the description of some of their hypotheses. This is the first step of data publication and it is a first basis for discussion. This first step already requires a large amount of work, particularly for popularizing the results (see section about popularization).

The present framework suggests ways for scenario producers to report their activities, hypotheses and results in a collectively more efficient and transparent way. The effort to follow the framework might not only be about the amount of information to provide, but also about its quality and its proper organization within the final report. Instead of being segmented across the report, key ideas could be efficiently described and justified in their dedicated sections. For complex concepts and systems, new ways of describing them could efficiently convey the core intelligence. Our framework extensively talk about this first level of transparency.

b. A deeper data publication is necessary for a healthy energy transition debate…

The first level of data publication may not be enough for building trust among the scenario community. A deeper data publication could be achieved, through the complete publication of exogenous data as well as endogenous data.

Exogenous data are particularly important as they gather the main assumptions which are embedded in the model and the ones which define the different scenarios. This set of data can be heavy, because the modeled system is very complex and is described through thousands of parameters, each having the possibility to evolve through time. Hence publishing the whole set of data can be cumbersome. It has to be properly set up, in the right format

[16] In France, the National Debate on Energy Transition, held in 2012, required to set up a group of experts which had to gather existing studies, get in touch with scenario producers, ask them to provide data in a standard way, and discuss with them in order to provide a transition map.

file for it to be readable, and must be extensively documented so the reader can know the meaning of the different variables. Often exogenous data (exogenous variables and parameters[17]) are not directly collected by scenario producers: they come from other public, or private sources. If they are publicly available, referencing those references does fulfill the publication task (assuming the referenced source has properly performed the publication and documentation of its data). In the case they are not publicly available, there publication is required to ensure a deeper transparency.

For the same reasons, publishing all the endogenous variables[18] can be cumbersome.

In addition to data publication, data documentation is extremely important for the scenario community to:

- Be able to discuss the data, propose better data and share data
- Be able to reuse the published data in a proper way in further studies, as exogenous variables or for results comparisons

In other words, publishing the data without documenting them is not useful for the scenario community: both data publication and documentation are important.

Crucial aspects of data documentation are the following:

- Coverage of the documentation: documentation should deal with all the published variables
- Nature and unit of the variables. For example, amounts of oil can be described as a volume or as a mass, each with different possible units (for instance, gallons, liters, barrels, cubic meters etc, for volumes)
- Perimeter of the data: it corresponds to the perimeter over which the variable has been measured (within the model for endogenous variables, or in the real world for exogenous variables). This perimeter can be geographical (what locations are included in the measure?), functional (what elements are included in the measure?) or time related (over which period of time is the measurement performed?). For example, an amount of sand required to build wind turbines can be measured over different geographical areas. It can also be measured over different functional scope: for example, the scope can be the tower and turbine only, or it can also include the foundations, or it could even include the road which had to be built to access the turbine. It can be measured over different time scopes: for example it can be the consumption of year 2023 or the consumption over the years 2026-2031.

Data publication and documentation are one of the main building blocks of a scenario community, as they are the only solid basis over which discussion, sharing, and cooperation can happen. In this respect, for scenario communities to emerge, strengthen and interconnect, business models must be found for energy system data providers to publish their data. The main barrier to such practices is that the publication of some data could go against commercial interests or intellectual property of legal entities.

As of today, many studies are largely "model-driven". Indeed, many scenario producers do not have access to in-house modeling capacity, so they have to buy modeling services. They usually use off-the-shelf models which already embed huge amounts of data about the national energy systems, there evolutions and the ways they operate. In these cases, embedded data may be privatized and their access may be restricted or subject to a fee. Scenario producers may not have the right to publish these data (or they would undergo important penalties) even though they are contributing to a public debate. This raises the question of the collective transparency which is required in such an important debate as the one about the energy transition.

Data can be practically unpublished but theoretically available. As publishing and documenting every data takes time, scenario producers might prefer to provide data and explanations when asked to. This activity can then feed a Q&A page on a website. However, this solution supposes a perfect knowledge management over time within the scenario team: if someone asks data documentation two years after the study publication, someone in the scenario

[17] see box below and Figure 7 for definitions: exogenous variables and parameters are those data which are assumed in the model not to be affected by any other variable, but to have an effect on other variables.
[18] see box below and Figure 7 for definitions: endogenous variables are those data which are assumed in the model to be affected by other variables or parameters.

team must be able to answer even if the person who handled the data at publication time is not part of the team anymore.

c. … Along with a greater model transparency

Just as data can be published to various degrees, model can be disclosed in several ways:

- Explain the model, and compare its main differences with other models, through text and diagrams. This method requires simplifying the model, hence it requires experts' choices about what to include in the simplified description (see next section). Making explicit the differences between the model and others enables a quick understanding of the main simplifications and limitations of the model. These methods might be the best way for the greater public to understand the global structure of the model and its main assumptions and limitations. Simplified explanation is already tentatively performed in most scenario reports.

- Give access to the modeling functionality by letting people use the model. This method enable the greater public to test their own assumptions with the model. However, such an access does not seem to be an efficient way for understanding the structure of the model, as it would require a large effort of retro-engineering, such as designing a set of experiments to investigate the links between variables. However access to model functionality is important for trust building among the scenario community and towards the greater public.

- Publish the source code: models of the energy transition are highly complex, and code reading requires knowledge and skills in algorithm science. Understanding a model through reading the source code would require a lot of time (probably more than a full time year for most complex models, which contain several tens of thousands of equations). Hence the complete publication of a model is not useful for the greater public to understand it. However it might be useful for getting expert feedback, and it is particularly important for trust building among the scenario community.

All these ways require time. Publishing a model requires time to give it the proper form and to ensure its readability.

- A model might be composed of several files, whose interactions must appear clearly. The code must be indented and commented.
- Explaining a model requires time for selecting the aspects to talk about, for writing about them and for designing explanatory diagrams.
- Giving access to the model functionality requires to design a user-friendly software/web platform enabling everyone to use the model, as well as the documentation for users to understand the features of this software/platform.

Some scenario producers use off-the-shelf models, whose documentation already exists. For example, the PRIMES model, used by (European Commission, 2011; SFEN, 2018) provides an extensive documentation (Capros, s. d.; Carpos et al., 2013). The ThreeMe model, used for the macroeconomic assessment of ADEME scenarios (ADEME, 2013) is described in a publication (Callonec, Landa Rivera, Malliet, Saussay, & Reynès, 2016).

Existing models may have been peer-reviewed, may have passed some validation tests (on some or all of its modules), or may be based on published research literature. In other words, existing models have a history within the scenario community.

Recommendations for scenario producers

A scenario strategy about transparency should be defined and justified (Cao et al., 2016). It should include considerations on the chosen level of data publication. The following aspects may be reported about:

- Exogenous data publication coverage, including referenced data sources. *How much of the exogenous data has been published? Why are some data not published? Are some of them already published by another organization?*

- Endogenous data publication coverage. *How much of the endogenous data has been published? Why are some data not published?*
- Data documentation completeness, including the amount of data covered by the documentation and the proper documentation (nature, unit, and perimeter of the data)

The strategy about transparency should include considerations on the chosen level of model publication. The history of the model (or some of its modules) in terms of peer-reviewing or validation tests should be described.

Is the model explained through simple text and diagrams and comparisons with other models? Is the model functionality publicly accessible? Is the whole model published through its source code? Is transparency of the model already ensured by another organization (the model producer)?

Has the model been peer-reviewed? What community did perform the review? Has the model been validated? Through which process? Is it based on existing literature?

2. Popularizing the model and its results

Popularizing the results of a scenario is explaining the results in a simple way. It is about describing the main determinants of the results according to the model. In other words, it requires to make a simple link between hypotheses and each selected result.

a. Making complexity simple takes a lot of time but is necessary for increasing credibility

This activity is crucial for the reader to trust the results. The influence of a study is much greater if readers can understand the results and their origins because the process of understanding is close to the one of accepting the results as true.

This can be achieved within two steps: first an expert needs to understand the result, second the explanation has to be rephrased for an easy understanding by the greater public.

The first step can be achieved by analyzing the model's internal variables so as to link hypotheses to results. Understanding the results can be achieved by exploring the emerging behavior of the overall model thanks to sensitivity analyses. Sensitivity analyses help finding the first order determinants of some results by varying variable parameters (see section II.D). Ideally, results should be accounted for by a few exogenous variables and a few model mechanisms. This process shows that the main results have been understood by modelers and scenario producers.

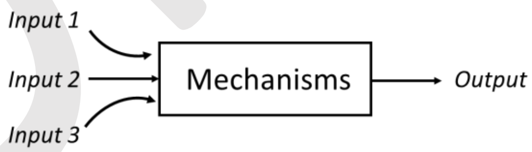

Figure 4: Ideally, main outputs should be explained by a few inputs (exogenous variables) and a few model mechanisms. Popularization can be achieved by explaining how these inputs interact in the model.

This activity is primarily performed by expert modelers as they know their model and are able to quickly detect the main drivers of particular results. This is why a great effort on skill maintenance through a good human resources management and an efficient knowledge management policy has to be made for using and maintaining complex models.

Usually model experts provide sets of data to scenarists with a first layer of interpretation (for example, explanatory slides showing the consistency and links between variables). Then scenario producers might add a second layer of interpretation, linking it to their driving question.

The second step can be achieved by setting up discussions between experts and non-experts who are responsible for writing the final report. During these discussions, experts have to reach the minimal amount of simplicity so non-experts understand the explanations and write them. Experts then have to proofread what has been written in order to ensure no key information is missing or no misunderstanding remains.

This whole process might be very time consuming and it may sometimes represent up to 25% of the total time spent on the study.

a. Model design should stick to the driving questions so as to avoid unnecessary complexity

Energy transition models tend to be complex due to the nature of the modelled system: the energy system is complex per se. A large number of concepts might be represented in the model, leading to a high number of modeled interactions between them. As a result, modeling and running durations as well as associated costs can be high. Achieving transparency and popularization is also more difficult and time consuming than with simpler models. Finally model use, maintenance and updating are difficult and require a continuous expertize associated to the model.

Hence in principle the model has to be as simple as possible while still being able to answer the driving questions. Driving questions determine model complexity, which determines how difficult popularization will be.

Recommendations for scenario producers

A scenario strategy about popularization should be defined and justified. It should include considerations on results interpretation and model explanation. The following aspects can be reported about:

- Main drivers of the results. *Are important results simply explained through (a few) links between key hypotheses, key model mechanisms and the results?*
- Results still to interpret. *Are some important results not understood yet?*
- Model complexity. *When selecting, or designing the model, have complexity and popularization aspects been taken into account? Could the model be simpler? How?*

3. Credibility can be fostered through disclosure of interests, **stakeholders' involvement** and disclosure of study limitations

Scenarios should disclose any conflict of interest. As commonly performed in the research studies, disclosure of interest is even more crucial for scenario production as future studies deal with the future of societies and as they are political objects by nature. Particular interests should have as low an influence as possible in the scenario production activities.

As part of this disclosure, organisms producing future studies should clearly and exhaustively state their funding sources (Cao et al., 2016). They should also disclose the financial interests of each participant to the study (within the core team but also consulted experts, proofreaders, etc).

A strategy to minimize conflicts of interests and to increase credibility is to involve experts and stakeholders with various interests in a participatory approach to define the study strategy and to follow the scenario production work (this has been performed in (CIRED, RAC-F, 2012; RTE, 2017)). For example, a panel of researchers and academic experts, companies, NGOs, etc can be consulted during the strategy design phase of the study and consulted again at halfway through the study during which the first results are presented and feedback from the experts is gathered and taken into account. Citizens can also be invited to these participatory sessions. Such a process must be participatory as opposed to solely consultative in order to foster trust among the participants.

A challenge for many scenario producers to engage in a participatory approach is to manage to talk the same language as stakeholders. Many scenario producers use a "model-driven" language to communicate their scenarios, which is not often adapted to discussing with stakeholders.

The reason is, many models are originally designed to bring information about the link between economic activity development and its associated impact on climate. They would start from aggregated activity growth hypotheses and then, for example, optimize the technology mix to show how to fulfill this growth while minimizing cost and respecting a carbon constraint (see section on energy consumption). Furthermore, models were designed to bring information about the design of highly centralized energy subsystems governed by a very few actors (such as the State): sizing and technology mix of the power system, the gas system and so on.

The downside of these design choices is that it is difficult to communicate and share hypotheses feeding the model, and results from it, with decentralized stakeholders (all the economic agents can be considered as stakeholder of energy transition scenarios, that is, individuals, households, companies, States…).

Many scenarios are model-driven and as such they are not adapted to create discussion about individual behavior changes, about companies' strategies, about employment, or about the desirability of the transition for the different actors, because the handled indicators (would they be endogenous or exogenous from the model point of view) are too aggregated to provide a concrete sense of the transition for individual stakeholders. It requires extra-steps, and extra hypotheses, to go from model variables to more "concrete" variables. For example, a hypothesis about the annual growth of car kilometers travelled (or the amount of energy consumed for travelling) does not say much about who will drive more, for what purpose, if those people once used to ride other modes of transportation and so on. Revealing why this aggregate variable would grow requires to take extra-hypotheses about mobility environment and behaviors; by doing so, a storyline has to be produced on those elements and is translated into figures which lead to the aggregate variable feeding the model (Briand, Bataille, & Waisman, 2018). This storyline provides stakeholders with a clear sense of what happens in the scenario, so that they can better discuss the different elements of the scenario.

Finally, including a section listing all the limitations of the study can help increase the credibility of the study. This practice is already adopted by some studies such as (ADEME, 2015; ADEME / Artelys, 2018; European Commission, 2011).

Recommendations for scenario producers

Organisms producing future studies should clearly and exhaustively state their funding sources.

All members who participated in the study (individuals as well as the organizations they represent) should be explicitly listed along with their potential financial interests linked with the study.

Scenario producers should report about how stakeholders or experts have been included in the study production process.

Scenario producers should report about the limitations of their study in a dedicated section of their report. Limitations can be detected through expert knowledge or any other means such as the present guidelines.

II. Study strategy is the ID card of a future study

The study strategy starts from the driving question(s), draws the overall plot around the energy system evolution, the main mechanisms making the mix evolve, and it defines the highlights of each scenario.

Giving access to a good, transparent description of a study strategy enables an understanding of 80% of the study with only 20% of the time that would be required to understand all of it. In a word, the strategy of a study is its overview, its ID card.

A. Scope and common storyline are the backbone of a study

The scope of a study is composed of the time horizon, geographical and sector perimeters, as well as start-year situation (greenfield versus brownfield).

The common storyline gathers the main hypotheses which are applied to all the scenarios of the study.

1. Time horizon: a crucial trade-off between energy system inertia and action urgency

2050 is often considered as a standard time horizon. This date is nonetheless questioned as a long-term horizon: (World Energy Council, 2016) chose 2060 as its time horizon while (SFEN, 2018) designed two scenarios with a time horizon of 2070. Indeed time horizon results from the addition of the start-year date and the timeframe of the study. The closer we get from 2050, the more studies will select time horizons beyond 2050 (this will be even more true if the transition is slow).

Time horizon is a choice serving the objective of answering the driving question(s) efficiently. Hence it is linked to the audience and the decision processes which are targeted by the study. Time horizon is part of the storyline, and greatly influences it.

a. Inertia of the energy systems and required magnitude of changes drives time horizon choice

Scenarios can be distinguished by their time horizons: short-term, medium-term and long-term scenarios can be defined.

Some processes which are considered in scenarios have much inertia: long-lived capital stock transition, technology emergence, population (through demographics). Their inertias have time constants of several decades. These processes determine the available stocks of long-lived capital, technologies, and people. Roughly speaking, only long-term scenarios can assume significant changes in these stocks.

The choice of time horizon implies constraints on infrastructure replacement magnitude and stranded assets. If time horizon is short, then replacing many infrastructure implies many stranded assets[19] (World Bank, 2009). Longer time horizons opens up more possibilities for system changes. Given the energy system inertia, a 15 year horizon is sometimes considered as short, opening up very few new opportunities. On the contrary, a 35 year horizon is considered as long enough to change significant aspects of it (Centre d’analyse stratégique, 2012).

Conversely, current investments in the energy system have lock-in impacts for 30-60 years. Hence informing current decisions in this domain requires future studies with long-term horizons.

Emerging technologies take time to become mature, so short-term scenarios cannot count on new technologies and they must propose technical solutions with known mature technologies. Longer-term scenarios can assume new technical problems will be solved with technologies not mature yet. These assumptions are part of the technological storyline (see section).

[19] Assets which are not fully economically amortized at the end of their lives.

Similarly, population structure evolves slowly. This constrains the available work force and the consumption evolution.

Some cultural traits might also be assumed to have an important inertia: it would take a long time to change them within a given culture.

In all of these processes, the inertia only comes from the fact that some elements of these stocks become "stranded" if the stock evolves too fast. Scenarios might accept to strand some elements of stocks under some conditions.

For capital stock, this translates into stranded assets. Some scenarios seek to economically justify the stranding of assets (for example, coal power plants) by internalizing externalities of those assets (for example, through a "carbon price").

Stranded technologies might also be considered (technologies becoming obsolete very quickly). However, to date, not one scenario considers "stranded people" (premature deaths or birth avoidance).

Stranded cultural traits might be an issue that scenarios consider. Some of them handle this question through the acceptance concept, which asks whether or not people can change some of their behaviors and habits in a given time (typically, consumption, and production behaviors – jobs). Justifying the stranding of cultural traits is usually performed through storytelling; however the proposed story might seem plausible to some and not to others, depending on each and everyone's believes about human nature and society evolution (see section on acceptance). Similarly to the economic theories, psychological and sociological theories are still various and are not shared among researchers.

Of course all those aspects take place from the start-year date of the study. This is why the start-year is an important information to take into account with inertia in order to select time horizon (see Figure 5).

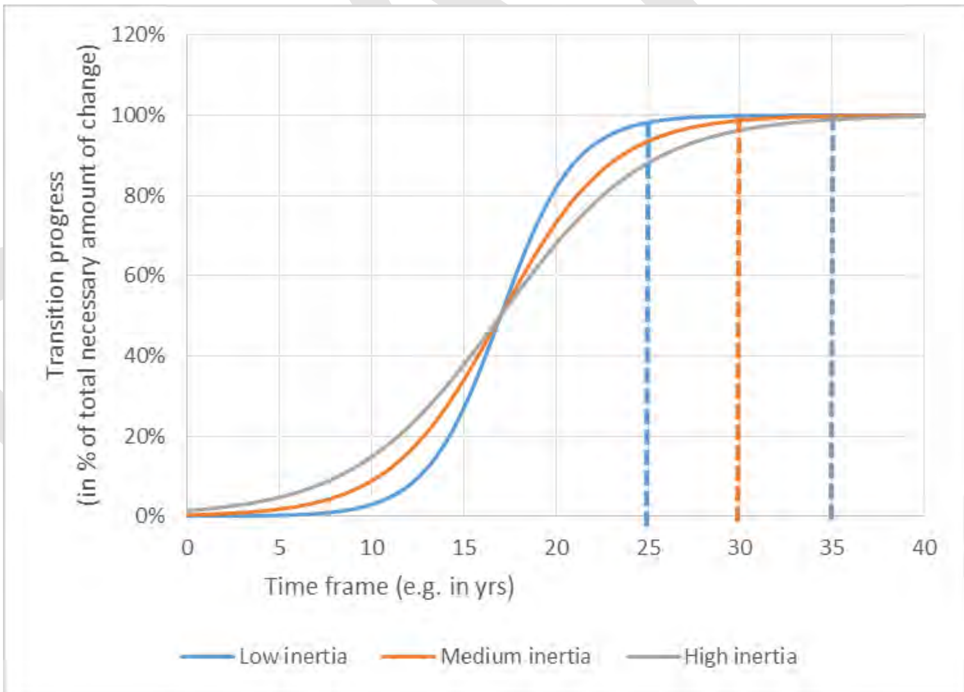

Figure 5: Illustration of what could be the minimal time horizon for different scenarios depending on the inertia of the studied system. Year 0 represents the start-year date. For the low inertia system, transition is quicker hence the time horizon could be as soon as year 25. On the contrary, for the high inertia system, transition is slower hence time horizon should not be before year 35.

b. Time horizon vs planetary boundaries

Most scenarios take into consideration GHG emissions. A large consensus about the urgency of reducing our emissions exists among researchers and scenario producers. This urgency requires a fast transition. Some scenarios, e.g. (Association négaWatt, 2014; ECF, 2010; World Energy Council, 2016) also evoke finite resources depletion, or other planetary boundaries[20] as drivers for transitioning (a review is performed in (Child, Koskinen, Linnanen, & Breyer, 2018)).

These considerations implicitly influence the choice of time horizon, as the greatest part of transition effort must be made before 2050.

c. Time horizon choice, as an arbitrary end to a scenario, distorts effort measurements and may fail to inform path dependency

Time horizon is the arbitrary end-date of a scenario. Current time horizons of medium to long term scenarios range between 2035 and 2070.

Putting an end to time is not realistic (in the real world, to the best of our knowledge, time will not stop). This end-of-time effect, or *horizon effect*, affects the practical way of measuring the transition efforts (RTE, 2017). Indeed, if the energy transition ends just before time horizon, many infrastructure will still be useful decades after this end. The costs might be the same as in a less efficient scenario in which the transition is not achieved, with many old infrastructure in need to be replaced just after the end date. Despite their equivalent costs, these two scenarios would not have the same value for society (see section on economic evaluation).

Even worse, time horizon can hide some negative path dependency. A case in point, a scenario depicting a transition which involves a massive increase in lithium consumption and a lock-in in high consumption habits. If the time horizon is a few years before lithium constraints turn critical, the scenario fails to see the described pathway is not sustainable for society.

Such effects are described in (CGDD, 2016) which shows that optimal pathways are qualitatively different depending on the chosen time horizon. This study explores the actions to be undertaken and in which order to implement them in a cost optimal way in order to reach a CO2 emissions reduction target by 2050. After running a scenario until 2050, the CO2 emissions reduction obtained by 2030 was recorded, and the model was re-run with 2030 as new time horizon and the recorded reduction as new target. The results between 2016 and 2030 were different between the two runs. For example, in the mobility sector, electrical and hydrogen cars start developing before 2030 when the time horizon is 2050. But if time horizon is 2030 with an intermediary CO2 objective, thermal engine cars are improved and electrical or hydrogen cars do not appear. In other words, the goal of improving thermal engine cars would lead to a lock-in effect, not preparing the industry and customers to more stringent objectives by 2050.

Recommendations to scenario producers

Time horizon should be explicitly mentioned, as well as start-year date. The time horizon choice may be justified with regards to such considerations as the driving questions of the study, inertia of the described system or planetary boundaries or any other urgency issue.

A strategy for handling horizon effects should be defined and justified. It should include considerations on properly measuring transition efforts and impacts given the horizon effect (see also section on economy). It should include a strategy to analyze path dependency and the risks of misinformation induced by horizon effects.

2. Descriptive perimeter: where the action takes place

The geographical perimeter corresponds to the area which scenarios of a study describe. Its infrastructure, the way its inhabitants live and consume, the operation of its production infrastructure, etc are described through time. This perimeter is called in this framework the *descriptive perimeter*. This perimeter may in some cases be difficult to describe because it is parceled out, or because usual terms to describe it are not explicit enough. For example,

[20] See (Steffen et al., 2015)

"European Union" or "Euro Zone" may be ill-defined because of their complexity (for instance, which French islands are included in these areas?).

Recommendations to scenario producers

The descriptive perimeter of the study should be explicitly mentioned. This perimeter should be precisely defined, for example with regards to territory parceling out. Its link with the driving questions may be explained.

3. Sector scope is what the scenario will report about

The sector scope refers to the set of activities within the energy system, or impacts on surrounding systems which are described in the scenario report. Not everything can be described within the geographical scope (for example, energy transition scenarios do not describe the number of times the word "hello" is pronounced each year in UK, or the evolution of this figure). Hence specific activities, or impacts, are described and sometimes modeled by the scenario producer in order to properly answer the driving questions. The scope encompasses all these activities and impacts, would they be hypotheses or results of the model.

Broadly speaking, scenarios which interest us can have different sector scopes.

However, they all consider some parts of the power system or the whole energy system as their *core systems*.

- Some future studies about power systems focus on the power system's supply side, that is, the components of the power system from power plants to final consumption, but excluding the device consuming the electricity (such as the lamp, TV set, industrial process, or electric car).
 In such studies (ADEME, 2015; ADEME / Artelys, 2018; Agora Energiewende, IDDRI, 2018; Lappeenranta University of Technology / Energy Watch Group, 2017), the goal is to propose an optimal power supply system. Power demand trajectory is fixed, and is not included in impact assessment. For example, the extra costs (if any) of replacing the ICE car stock by electric cars, or the cost of insulating buildings, are not considered even though they act on demand evolution.
- Some other studies (ECF, 2010; RTE, 2017) focus on the overall power system (supply-side and demand-side, that is, including the devices consuming electricity). In such studies, the overall effect of power demand evolution and power supply evolution can be assessed.
- Some studies consider the whole energy system (Association négaWatt, 2017; European Commission, 2011; European Commission, 2016; SFEN, 2018; SLC, 2017), including the supply-side and demand-side for each energy carrier (oil, natural gas, coal, heat and cold, etc),. These scenarios further study the interactions between carriers during the transition and provide an overall consistency across the carriers to fulfill energy demand.

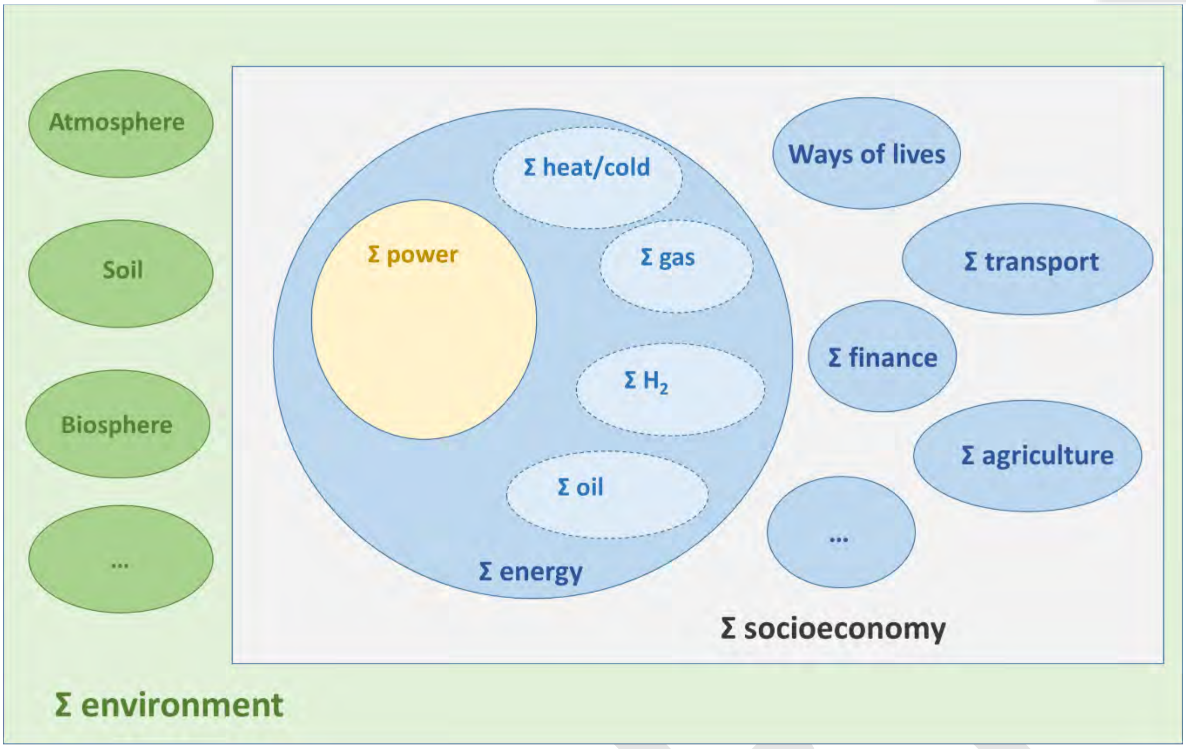

Figure 6: The scope of studies can include all or some aspects of the systems described in this figure. Core systems are included in the energy system. Other systems are considered as surrounding systems. The "Σ" symbol means "system" in this diagram.

Around those *core systems*, some aspects of *surrounding systems*, such as the economic system (including different markets, actors of these markets and the associated demands), society (including lifestyles, consumption habits, etc) and/or some aspects of the environment (such as GHG emitted in the atmosphere, biosphere integrity and so on) are described (see Figure 6).

For example, (ADEME, 2015; RTE, 2017) focus on the power system, GHG emissions, and necessary expenses. (Association négaWatt, 2017; ECF, 2010; Greenpeace, 2015; SLC, 2017) focus on the energy system and GHG emissions. (European Commission, 2011; SFEN, 2018) focus on the whole economy driving the energy system and GHG emissions.

Recommendations to scenario producers

The sector scope of the study should be explicitly mentioned. The following aspects should be mentioned:

- Scope of the considered core system (power supply only / whole power system / whole energy system)
- Interactions which are considered between the core system and its surrounding systems (environment, ways of lives, finance…)

4. Greenfield approach can be used as a first step, brownfield approach enables to go deeper in the energy transition debate

a. Greenfield and brownfield situations: the possibility of changing an asset or not

In a scenario, a greenfield situation for a given asset is a situation in which this asset presents an opportunity to change. For example, when a power plant is decommissioned, there is an opportunity to replace it by another power production mean. A brownfield situation is when the asset is not open (yet) to change (Agora Energiewende, 2015).

Pure greenfield scenarios are scenarios in which all energy system assets are in a greenfield situation at the start of the scenario, as if the energy system could be built from scratch. In actual greenfield scenarios, depending on the driving questions, some assets are fixed by the scenario (such as the consumption devices, in (ADEME, 2015)) while some others are open to choice (for example the structure of the power system (PS) and the production plants in (ADEME, 2015)). Greenfield scenarios are sometimes called snapshots when the transition phase is not described. Indeed, the trajectory per se may not be interesting as it is not linked to the real current situation.

Brownfield scenarios fix all the assets of the energy system at start year, as measured in the "real world", and then these assets switch to a greenfield situation, typically by reaching their end-of-life[21]. However, scenario producers might choose other rules to create greenfield situations. For example, some scenarios might accept to close coal power plants before the end of their lives for CO_2 emissions reduction reasons (which assumes that past choices were not in line with the new objectives of the scenario).

b. Very long-time brownfield scenarios are not equivalent to greenfield scenarios

Even if on the long run all the unitary assets might become greenfield (for example, on the long-run, all the assets need to be replaced anyway, so all of them go through a greenfield situation), macro dimensions (such as the overall structure of the PS) might not become greenfield during the transition.

As explained by (Agora Energiewende, 2015): "The key difference between these two approaches is that in [greenfield scenarios], the entire system may be designed in the most cost-optimal way, including all interaction effects between different technologies. In [brownfield scenarios], a cost-optimal design of the existing system is not possible, which likely will lead to an altogether sub-optimal solution."

As an illustration, let us take 2 scenarios (a greenfield one and a brownfield one) in which the structure of the PS dramatically evolves from the current one, while ensuring the security of supply during the transition.

The greenfield scenario would directly implement the whole new PS, optimizing the costs to do so.

On the contrary, the brownfield scenario might require to maintain the current system before the new system is mature enough to operate on its own. This would lead to extra costs which are only linked to the transition pattern. For example, transitioning from a centralized PS to a fully decentralized one requires to carefully plan for the transition in order to ensure a continuity of the service through time. For example, an option for such a transition could be to transition through an intermediary waypoint: a decentralized PS backed by the centralized PS, such as the one described in (France Stratégie, 2017)).

c. The study of energy transition details requires brownfield scenarios…

Hence, generally speaking, the study of the energy system transition and of transition rates (for example, yearly investment in the energy system) requires brownfield scenarios because they model the path dependency and inertia of our energy systems.

Usually, studies involve only brownfield scenarios or only greenfield scenarios. Indeed, comparing a greenfield to a brownfield scenario would only inform about the extra effort due to the existence of the current energy system, compared to the fictive situation where the current energy system would not exist. This would not be useful for the energy transition debate. As a result, we consider that the brownfield vs greenfield distinction applies to studies rather than to individual scenarios[22].

[21] not amortizing an asset to its full use is sub-optimal in economic terms (stranded asset), hence assets are considered as greenfield again (available for being replaced) when they reach their economic end-of-life

[22] The distinction between a future study and a scenario is made in section II.C.2.

d. … But greenfield scenarios can help uncover important risks and barriers

Greenfield studies are nonetheless useful to explore limits and to uncover a part of the barriers that need to be overcome if these scenarios are to be followed. They cannot reveal all the challenges related to the transition process though, as transition per se is not within their scopes. In a word, such studies can be seen as prototypes design studies.

They can nonetheless be useful to study transitions under two conditions: the prototype energy system's global structure must be similar as the currently existing one, and the transition must be slow compared to the economic lifetime of the infrastructures within the scope of the energy system. When both conditions are fulfilled, it can be argued that building the proposed design from scratch would involve the same process as waiting that each individual infrastructure reach its end of life and then replacing it with the new infrastructure as in the prototype. In other words, waiting for each individual infrastructure to be in a greenfield situation in order to build brick by brick the prototype.

Recommendations for scenario producers

The choice regarding the start-year situation of the study should be made explicit: greenfield or brownfield. This choice should be justified with regards to the driving questions of the study.

The overall strategy about how greenfield situations happen in the scenarios, that is, under which conditions assets can be changed, should be reported about.

5. Common storyline

In addition to the scope elements, all the proposed scenarios share a common story about different aspects of the energy transition, that we call the *common storyline*.

The common storyline might be about the different types, and characteristics, of plants in place at start year in the considered geographical perimeter, the parameters under which they evolve in the scenario and the different technologies which are introduced in the scenario (for example the annual rate at which different technology costs decrease are invariable data in (ECF, 2010)). Parameters about the geographical location of the different generation plants at start-year, transmission and distribution networks might be described. Parameters about the climate(s) within the geographical perimeter might be common to all scenarios (climate chronicles from Meteo France are used in (RTE, 2017)). The demographics, or some important cultural traits, may be the same across scenarios. These parameters set the overall, fixed frame which does not vary across scenarios. They form what (World Energy Council, 2016) calls its central scenario (even though the central scenario might not be extensively described).

The elements of scope common storyline are common to all the scenarios in the study. In this prospect, they are the backbone of the study. They are translated in the model into *invariable parameters* (see box below and Figure 7).

Understanding the use of variables in scenarios

Understanding the way a model operates is very useful to grasp the important concepts of a study strategy. Indeed, the study strategy is always translated into a computational model.

Roughly speaking, a model puts into play a set of variables (which evolve through the timeframe of the scenario). These variables can be fully defined before the model does any calculation: they are then called exogenous variables and parameters, or the hypotheses, of the model.

The other variables are computed by the model, hence they are its results. These variables are called endogenous variables (see figure below, which is completed by the following sections).

Considering a variable endogenous, or exogenous, is a choice which depends on the modelling capacity and on the link between the modelled system and the variable, within the time frame and geographical scope of the study. If the variable is assumed to have an effect on the modelled system while not being affected by what happens within the system, then it is considered as an exogenous variable or a parameter.

For example, European demographics is usually considered as largely independent from the European economic and energy systems. Hence the assumption is that this variable depends on no other variable in the model: it is taken as an exogenous variable in most European scenarios (ECF, 2010; European Commission, 2011; SFEN, 2018). Sometimes population is not even in the storyline. Instead, GDP is considered as the main input for determining demand (such is in (Imperial College London, NERA, DNV GL, 2014)). As a result, these scenarios do not inform about the effects of severe crises, such as a massive heatwave, or power outage[23] which would affect Europe's population. However, demographics could be made endogenous (such as what is famously performed in (Donella H. Meadows, Randers, & Meadows, 2004)): endogeneity, or exogeneity is a choice from the scenario producer.

Similarly, fossil fuel prices are often considered as exogenous variables for European scenarios, Europe assumingly playing little role in the shaping of fossil fuel world prices.

Yearly CO_2 emissions are always considered in future studies as endogenous variables, as the energy system directly produces them; emissions are computed based on the modelled operation of the energy, food, and/or economic, systems.

The expenditures for the energy transition are also always considered as endogenous. The assumption is that money transactions are the results of decisions (from the benevolent planner or economic agents, as explained below) coming beforehand. Transition expenditures are computed from the various expenditures in the energy system along the scenario.

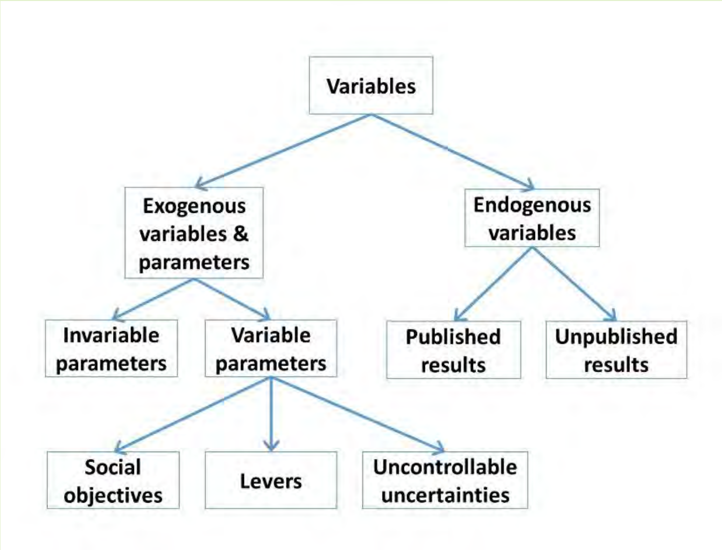

Figure 7: The different categories of variables used by scenarios. Each category is detailed in the following sections.

Recommendations for scenario producers

Recommendations are provided in the section II.C.4 about the storyline.

[23] See (Mark Elsberg, 2017)

B. Models are described along two philosophies: benevolent planner, or simulated agents

The philosophy of the model which will be used is also common to all the scenarios[24] in a study. The most salient feature of energy models, which we call the *model philosophy* lies in what drives the energy mix[25] evolution in the study, and how it does it.

The energy system is influenced by two distinct processes (see Figure 8). A long term control process, including infrastructure investment decisions, or any regulation, tax, subsidy, leads to the long term evolution of the energy system. As for the near term control process, it corresponds to the energy system operation mechanisms: market operation, demand daily evolution, automated and manual control by DSOs and TSOs, etc.

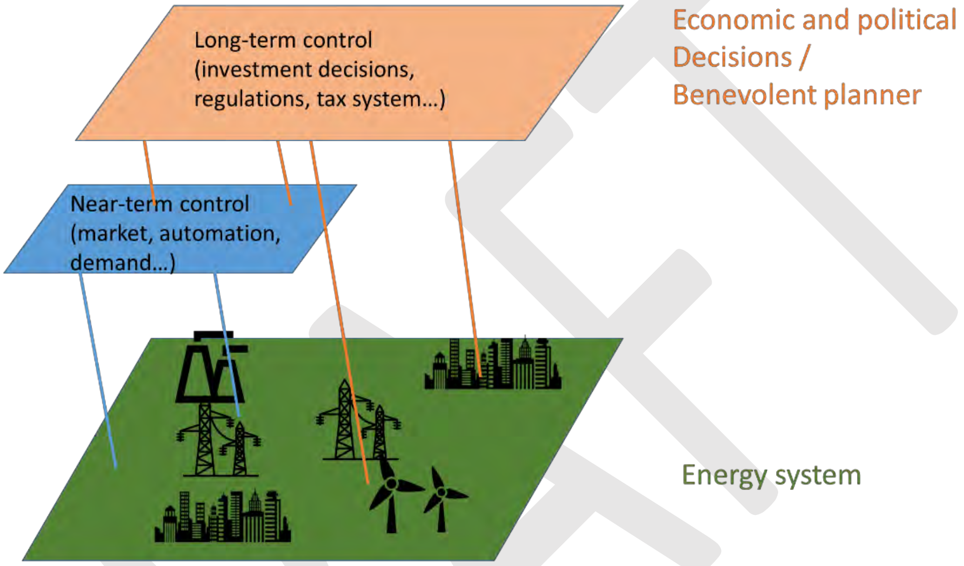

Figure 8 : the energy system is controlled through a long term control process and a near term control process. Future studies use two different ways to model the long term control process: either economic agents decisions are simulated, or a benevolent planner decides.

a. Simulated agents or benevolent planner?

This long-term control process can be modelled by decision agents representing the economic agents. Those agents make investment decisions based on regulations, tax system they are submitted to, such as in (European Commission, 2011; RTE, 2017; SFEN, 2018).

The long-term control process can also be modelled by a "benevolent planner" who makes decisions based on a global knowledge of the energy system (and sometimes its future), through design rules. Usually, the benevolent planner optimizes the global costs of the transition (least cost optimization) while maintaining the yearly energy supply and demand balance, such as in (ADEME, 2015; ECF, 2010; World Energy Council, 2016). But other planners might want to define the greater good of society through other rules. For example, planners can favor anytime possible, and up to a defined certain limit, sobriety, then energy efficiency, then renewable energy sources (RES) development while decommissioning nuclear plants (Association négaWatt, 2014; Association négaWatt, 2017), or any other rules (Fraunhofer ISE, 2015; SLC, 2017).

In the first case, we say the energy mix is driven by *simulated agents* whereas in the second case, we say it is driven by a *benevolent planner*.

[24] Except in some specific studies such as (Bovari, Giraud, & Mc Isaac, 2018)
[25] the assets composing the energy system

b. Modeling the economy: a tradeoff between operationalization level and consensus level

As a result, when a benevolent planner decides, the economy is not modelled: only the energy, or power system is modelled, even though economic indicators can be drown from those studies (for example, cost assessments of the transition, or the costs decompositions between different components of the energy system). In the benevolent planner approach, the level of operationalization of the study remains at the energy system objectives level: only recommendations about how the energy system should, or should not, evolve can be inferred from the results.

On the contrary, in the simulated agent approach, different economic actors are represented, so that parts of the economy are modeled, such as actors who finance energy projects, or different energy consumers. Hence these studies can model the reaction of the economic agents to different economic or policy levers. In other words, the operationalization level of the study can be higher: recommendations can be about economic or political levers.

However, there is a fundamental difference between those two approaches. The benevolent planner one is based on physical equations which are largely consensual among experts whereas the simulated agents one is based on a vision of how the economy works – a vision which is not consensual among economists (IDDRI, 2013).

(see section on models)

Recommendations for scenario producers:

The strategy about the long-term control of the transition should be defined and justified (with regards to the driving questions, to modeling constraints, etc). The different aspects of long-term control of the transition which are considered should be reported. The following aspects may be reported about:

- The nature of the deciding agent(s): benevolent planner or simulated agents. For simulated agents, the main ones should be listed. Financers, demand from households, industries...
- The important rules governing the behavior of each of those agents. *For example:*
  - o *Does the benevolent planner act through a minimization of the total expenditures induced by the transition? Does the benevolent planner minimize total expenditures under some constraints (for example maintaining security of supply, or decreasing CO2 emissions by 80% by 2050)?*
  - o *Do simulated agents can try to maximize their profits or utilities? How do they each do it? For example, what discount rate private or public actors use? What rationale do households use to make their consumption choices?*

***

These elements (scopes, common storyline, model philosophy, published results) are actually not selected out of thin air but are partly data-driven: if no data, or methodology exist on a particular aspect, modeling this aspect requires a time consuming work beforehand. For example, modeling global impacts of the economy on biosphere integrity would require a precise enough biosphere model, which would require a long data collection work about biosphere and the way it functions. Similarly, the lack of data about how economic agents finance energy projects can drive the philosophy of the model towards a benevolent planner approach.

C. Highlighting the common points and differences between scenarios within a study is key

Within each study different scenarios are imagined and compared in order to answer the driving question(s). Scenarios differ from each other because they each activate different levers, set different objectives for society or explore different ways uncertainties might unfold in the future. The following subsections explore these aspects which differentiate scenarios within a study.

1. Scenarios differ from the levers they activate, the society objectives they set and the uncontrollable uncertainties they explore

Going to the model side is interesting to understand how different scenarios fundamentally differ from each other in studies:

In models, an (exogenous) parameter is deemed variable by scenarists when the driving question asks to explore the effect of its variations. It can be considered as an interesting, controllable *lever* by the question, as a controllable, desirable *society objective* society would set to itself, or be seen as an *uncontrollable uncertainty*. These parameters are made to vary across the different scenarios.

- Some controllable parameters are considered as *levers* in studies. For example, the planning question might be to explore the effect of an extended policy package on CO_2 emissions, compared to the planned package (such as in (European Commission, 2011)). The scenarists would compare CO_2 emissions between a scenario in which the extended package is implemented and a scenario in which the regular package is implemented. The extension of the package is considered as a lever to alter CO_2 emissions. The question "What would be the implications of reaching a divide by 4 of CO_2 emissions in France through more RES, energy sobriety and energy efficiency, for the environment, the economy, lifestyles, research activities and energy industry activities? [26]" defines RES share, energy sobriety and energy efficiency as controllable input parameters. (Association négaWatt, 2017) adopts such levers.
- Objectives of the benevolent planner or of society are another type of controllable parameters. Typically, the end-year objective(s) in backcasting scenarios are such objectives (see section of type of scenario). They are called *social objectives* here.

  We consider they are variable parameters when they change across scenarios in a same study. Indeed, in this case, they are inputs to the model that vary across scenarios.
  For example, (ECF, 2010) has three scenarios each with a different objective for CO2 emissions reduction (-40%, -60%, -80%). The reduction variable is a social objective.
- The *uncontrollable uncertainties* (which (Cao et al., 2016) call "uncertain factors") may lead scenarists to define alternative scenarios, around a central scenario, as a way to show the effect of choosing other values for these uncertainties. For example, demand evolution, or energy import prices may be deemed uncertain and lead to several hypotheses and several alternative scenarios. (European Commission, 2011) defines a "high energy import prices" scenario and a "low energy import prices" scenario. The study (Agora Energiewende, IDDRI, 2018) defines a "low nuclear", "medium nuclear" and "high nuclear" scenario. Such alternative scenarios are a way for scenario producers to show the possible outcomes over an uncertainty range for some variable parameters. Scenario producers choose a range that they judge plausible for their uncontrollable uncertainties, out of which they do not get.

  Sometimes the planning question uniquely investigates uncertainties: "Assuming a given global demographic evolution, the spread of given technologies, the reality of planetary environmental boundaries and a shift of power towards China, how can the world energy system evolve by 2060?". In this case, no lever is defined, but some uncontrollable uncertainties are. In this example, innovation and productivity levels, world governance trends, climate change action magnitude, and the share of market-based versus state-based tools use are defined as the uncontrollable uncertainties. From all the possible combinations of values for these parameters, three combinations are selected by World Energy Council scenarists, defining three derived scenarios (World Energy Council, 2016).

Recommendations for scenario producers:

Study strategy about scenarios' fundamental definitions should be defined and justified with regards to the driving questions. Specifically, the dimensions which differ between the different scenarios should be detailed and the nature of the differences should be explicit (lever, social objective or uncontrollable uncertainty).

[26] This planning question is implicitly asked in (ANCRE, 2013)

2. Different study structures to convey different messages

A study can involve one, or several, scenarios which taken together bring answers to the driving question(s). We observed a variety of structures for arranging the different scenarios together:

- The most basic structure for a study is the "one scenario structure" (such as in (ADEME, 2012; ADEME, 2017)). The study is composed of a single scenario which is detailed. The results are implicitly compared to our current world and standard of life. For example, (ADEME, 2012; ADEME, 2017) describe behavioral, organizational and infrastructure changes in mobility, freight, building and agriculture leading to a 75% reduction in CO2 emissions. This provides a way to describe society during the proposed transition, compared to the current society. This structure is useful to tell the story of a transition. In this regard, ADEME published a sociological report to make the story more concrete for people (ADEME, 2014).
- A second possible structure is the n vs 1 scenario structure (see Figure 9). In this structure, n scenarios are designed based on one of them which is defined as the *reference* scenario. The n scenarios activate different levers/set different social objectives/consider different values for uncontrollable uncertainties, which are not activated/set/considered in the reference scenario, in order to assess the effect these differences.

  The reference scenario is often considered as a *Business as usual* scenario, that is, a scenario in which no society, cultural, economic trend, or any human activity activity at any level, is significantly changed from today's, leading to a roughly steady energy system. In contrast, the other scenarios are often considered as *transformational* because at least one (most often several) of those trends or activity is significantly modified, significantly modifying in turn the energy system. Note that the reference scenario is a scenario per se.

  Such a structure is used by (Association négaWatt, 2017), in which the "négaWatt scenario" is compared to a reference in a 1 vs 1 structure. The négaWatt scenario implements a systematic choice towards sobriety, energy efficiency and renewable energies, as well as a nuclear phase out, compared to the reference; in (European Commission, 2011), 6 different scenarios implementing different packages of measures are compared to a reference scenario in which no measure is taken. The different packages contain measures favoring energy efficiency, renewables, nuclear, CCS, or a mix of them; in (ECF, 2010), 3 decarbonation pathways are derived from, and compared to a baseline scenario, each of them differing by the amount of RES in the power production; (ADEME, 2015) compares a tens of scenarios to a baseline one.

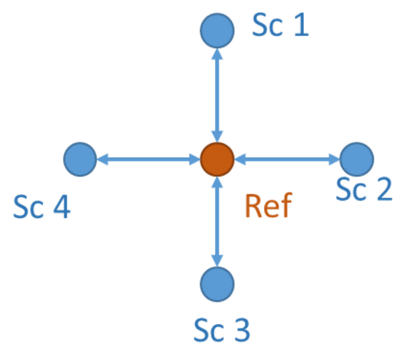

Figure 9 : Illustration of a 4 vs 1 scenario structure, where 4 scenarios are designed from a reference scenario, and are compared to it.

- An "n vs n scenario" structure can be observed in the literature. In this structure, all the scenarios are compared to each other (see Figure 10). The n scenarios might have very loose links between them, a large number of variables being different from each other's.

  The study (World Energy Council, 2016) has a "3 vs 3 scenario" structure as it defines a theoretical "central scenario" which is a common basis for all the scenarios. The central scenario serves to build the other scenarios, but is never simulated and no results about it is presented: it is not a scenario which is used as a comparison reference. The other scenarios (Modern Jazz, Unfinished symphony and Hard Rock) are simulated and compared between themselves.

(SFEN, 2018) has an "n vs n scenario" structure, as it compares 8 different pathways together, none of them being a reference scenario from which variations are introduced.

Similarly, (RTE, 2017) has a "4 vs 4 scenario" structure (comparing Ampère, Hertz, Volt, Watt scenarios).

This structure is useful to describe different, separate possible evolutions and compare them. The effect of single levers, or uncertainties, or social objectives, is not studied.

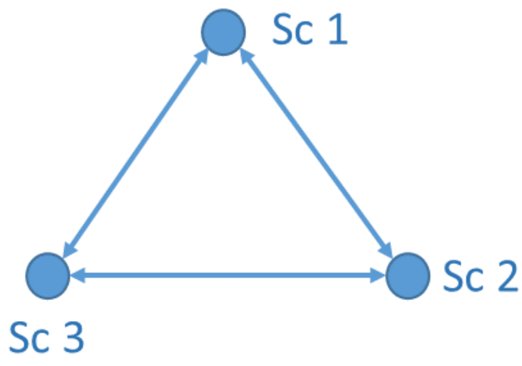

Figure 10 : illustration of a 3 vs 3 scenario structure, where three scenarios are compared with each other.

- Hybrid and more complex structures can be proposed, such as the one in (IIASA, 2012). This structure is based on a branching points rationale: a first branching point defines the level of demand (High, medium or low), the second one defines a dominant energy vector family (conventional fuels, or advanced ones), the third one being the supply-side portfolio.

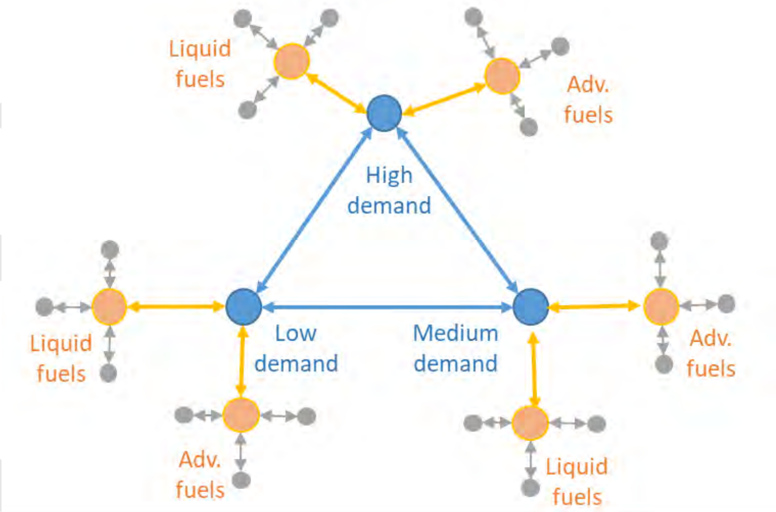

Figure 11: Structure of the (IIASA, 2012) study based on a branching points rationale.

Such a structure enables a systematic exploration of the transition map.

- Other structures can be imagined: for example, the study (Bovari, Giraud, & Mc Isaac, 2018) has a very special structure, as it compares the outcomes of different models rather than the outcomes of a single model with different variable parameters. In this study, each scenario is simulated by a different model testing new links between driving forces. For example, productivity is endogenous in the reference scenario, is linked to growth in the "Kaldor-Verdoorn case", and is linked to the average increase in atmosphere temperature in the "Burke et al." case.

It differs from the "n vs 1", or "n vs n" structures, because in these structures the same model is used for each scenario, that is, the same links apply between driving forces.

Recommendations for scenario producers

The study structure should be made explicit, and the choice of structure should be justified with regards to the driving questions. *For example, why a 2 vs 1 scenario structure has been selected?*

If a reference scenario is included in the study, this scenario, as any other scenario, should comply with the recommendations which are formulated in this guideline, ensuring its internal consistency.

3. Scenarios are studies' tools to explore consistent ways the future of the energy system may develop

A scenario is a description of a consistent energy system, economy, or whole society and of its evolution. Scenarios are future studies' tools to investigate the inner-consistency of different evolutions over a geographical scope and timeframe. The links between the different elements within the sector scope must be consistent; for example, lifestyles and cultural trends, technological progress, resources availability, environment, institutions consistently co-evolve within scenarios. Scenarios are not forecast tools; they are tools to explore how consistent futures could develop.

Scenarios are each broadly defined by a *storyline*, which is then translated into figures feeding the model, in order to get quantitative results. Through this process they can tell internally consistent, stories and quantitatively compare them in economic, technical, social or environmental terms.

Another added-value of scenarios is that they ensure the time consistency of stories. They represent transition processes and check the dynamical consistency between short term and long term decisions (IDDRI, 2013).

4. Storyline ensures the consistency between the hypotheses of a scenario

Storyline ensures the consistency between all the exogenous parameters of a scenario (both variable and invariable parameters). As the variables are exogenous, no consistency between them is ensured by the model. This is why it is of the highest importance to ensure this consistency through a proper, plausible storyline.

a. A storyline is a dynamic story

The storyline qualitatively describes the overall context in which the studied system evolves over the study timeframe. It is usually a textual, internally consistent, description of this evolving context. The storyline gathers the main hypotheses feeding the model. *Scenario storyline* is the specific story associated with one particular scenario: it completes the *common storyline* with the scenario's specific details. Hence it corresponds to the qualitative description of variable parameters (see Figure 7) and it ensures the qualitative inner consistency over the exogenous variables (Cao et al., 2016).

b. The content of the storyline depends on the sector scope of the scenario...

The sector scope defines the studied system; as such, it also defines what needs to be described about the context in which this system evolves.

For example, if the considered system is the whole socio-economic system (see Figure 1), then some characteristics of the environment that have an impact on the evolution of the socio-economic system over the scenario time horizon should be described (its most important characteristics being the so called "planetary boundaries" (Child et al., 2018)). They form the storyline and might be derived into exogenous hypotheses and model mechanisms (such as global warming damage curves).

If only the energy system is modeled, then the storyline may for example describe (in addition to the environmental context) the socio-economic trends impacting the energy system over the time horizon of the scenario, including:

- demographic trends,
- political structures and decisions: regulations (for example nuclear phase-out), taxes and subsidies (such as CO_2 price, feed-in tariffs), etc.), considerations on governance (subsidiarity, centralized *versus* decentralized decisions),
- economic trends: market evolutions, business models, finance evolution etc,
- technology development: new technologies, technology technical improvement or cost reduction,
- cultural trends (such as growing environmental concerns leading to consumption decrease, or a growing average willingness to phase out nuclear power, or household insulating their houses, etc)
- demand drivers

If only the power system is modeled, then the storyline describes (in addition to the previous elements) the trends on the other energy systems, such as the evolution of gas, hydrogen, heat, cold, or oil consumption.

c. ... But also on the geographical scope of the scenario

Finally, the storyline describes elements of context outside the scenario geographical scope which impact the considered system over the scenario timeframe. For example, if the perimeter is EU, considerations on the following elements may be described:

- energy transport infrastructures for exchanges with countries/ regions outside EU,
- trade with countries/regions outside EU,
- prices of imported goods, energy and technologies (such as the prices evolutions of fuels (oil, gas, coal, uranium), commodities, equipment)
- industry outshoring / inshoring.

Recommendations for scenario producers:

A complete and consistent storyline should be described for each scenario brought into play by the study. The storyline should define the framing elements of context in which the sector scope is evolving, that is, those elements which enable a good understanding of the system evolution.

The method used to produce the storyline may be described as well (Cao et al., 2016). *Has the storyline been designed through interdisciplinary workshops? Is it based on other studies' storylines?*

Those elements should be described over the whole study timeframe. They might be elements of other systems interacting with the studied system, or elements of the studied system but outside the geographical scope. Examples of such elements have been described hereabove. *For example, how does demography evolve through the study timeframe for each scenario? What about technology development or population environmental concern? What about power systems evolutions in regions around the geographical perimeter?*

1. The distinction between backcasting and exploratory methods is a matter of storyline

Scenarios are often described either as backcasting or as exploratory.

According to (ECF, 2010), [Back-casting method] stipulates the [objective] and then derives plausible pathways from today to achieve them. The end-state is stipulated rather than derived. A back-casting approach can help to highlight where momentum must be broken and re-directed in order to achieve future objectives, while forecasting: tends to extend current trends out into the future to see where they might arrive.

"Backcasting is a term introduced by Robinson: *The major distinguishing characteristic of backcasting analysis is a concern, not with what futures are likely to happen, but with how desirable futures can be attained. It is thus* *explicitly normative, involving working backwards from a particular desirable future end-point to the present in order to determine the physical feasibility of that future and what policy measures would be required to reach that point*." (Dreborg, 1996)

a. Backcasting components, exploratory components

A pure backcasting scenario would be a scenario in which the whole system at the end date is known along each of its dimensions before performing any simulation. Starting from that entirely defined system (its total costs are defined, its total CO2 emissions are defined, etc), the trajectories to reach it can be explicited (if ever such trajectories exist in the modeled world).

A pure exploratory scenario is a scenario in which no dimension of the considered system is known at the end date before the simulation. Hence the only way to know the system at final date is to run a simulation.

In practice, backcasting scenarios have both an exploratory component and a backcasting component. The backcasting component is the set of constraints on some dimensions of the final system. These constraints might be values to stick to, or thresholds to reach or not to reach. For example, yearly CO2 emissions might be supposed to get lower than a threshold at final year, keeping balance of trade for the area above a given threshold too. Security of supply might be supposed to be maintained up until the end of the scenario, etc. Their exploratory component is composed of the remaining, unconstrained at final date, dimensions.

Similarly, exploratory scenarios can have a backcasting component. For example, maintaining the electricity security of supply at a given level along the pathway is a backcasting component. However, the scenario is not considered as backcasting because this level of supply is already reached at the beginning of the scenario, and because this parameter seems to be a detail (hence it is difficult for it to be the reason of calling the end date a "desirable future").

b. The fundamental question is the one of the constraints at end-date

As a conclusion, the strength and importance of the backcasting components in a scenario seems to be the main factor of calling a scenario backcasting. As the strength and importance are subjective, the backcasting nature of a scenario may be subject to debate and may be linked to a specific storytelling from the scenario producer. More fundamentally, the audience of a scenario should understand which important dimensions are constrained at end-date, and what the associated constraints[27] are.

A constraint is usually quantitative[28], but it can be qualitative[29]. It can apply to aggregate values[30] or to a single variable[31]. It can be a target point, a target range, or a threshold to reach (for example, maintain security of supply for electricity above current level). It can apply at a particular time (for instance, by 2050) or during the whole trajectory (for example, maintaining security of supply over the whole scenario timeframe).

The description of these constraints is actually part of the storyline associated with the scenario. Indeed, backcasted components are social objectives, and as such they are part of the scenario storyline (Cao et al., 2016). For example, the objective of zero-net emissions over EU might be the consequence of a growing environmental concern.

Recommendations for scenario producers:

For each scenario, backcasted components should be reported in the storyline description (see previous section). The variables submitted to backcasting constraints should be mentioned, and the specific constraint be detailed. *For example, CO_2 emissions might be constrained to reach an 80% reduction by the end of the scenario, or*

[27] The word constraint is used here as a computational term meaning a variable must follow a constraint, but it might be called an "objective" by scenario producers.
[28] For example, (ANCRE, 2013) sets a target reduction of 75% of CO2 emissions by 2050
[29] For example, (Association négaWatt, 2017; Fraunhofer ISE, 2015; Greenpeace, 2015) have a nuclear phase out objective → mais c'est quantitative aussi non? (si on pense que nuclear phase out=0 nuke)?
[30] For example, (ADEME, 2015) sets different objectives of RES share in the power mix
[31] For example, (SFEN, 2018) sets an objective of 50% of nuclear power production in the French power production

renewables be constrained to reach at least 60% of the yearly power supply share by the end of the scenario. Electricity security of supply might be constrained to be stable over the scenario timeframe.

D. Discussing uncertainty helps to better understand the risks posed by some options and the ways to overcome them

The question here is on how to handle the deep uncertainty on the future. As (Carbone 4, 2014) puts it, there is no such thing as a "no-choice" situation when the considered horizon is 2050. In the next 30 years, many greenfield situations will appear and will call for choices.

Deep uncertainty can be tackled by exploring scenarios that span the range of uncertainties, through defining various scenarios (Guivarch et al., 2017), which is the goal of sensitivity analyses.

Another way is to ensure the scenario robustness to uncertainty through its storyline. Two different strategies are observed: either the storyline is conservative, or the risk is spread over several sources. These strategies are described in the following subsections.

1. Robustness by uncertainty exploration: the importance of sensitivity analyses

a. Sensitivity analyses explore the links between exogenous and endogenous variables

Technically speaking, a sensitivity analysis is the study of a set of dependent (endogenous) variables when one independent (exogenous) variable changes, from a main scenario.

The endogenous variables can be numerical parameters (the price of carbon, the number of house insulations per year, the cost of nuclear power…), or YES/NO parameters (the possibility to use such or such technology).

For example, (ECF, 2010) produces a European cost-optimized power mix respectively with, and without, the possibility of using demand response, and analyzes the differences between the obtained mixes (in terms of composition and costs). Similar analyses are done by reducing the transmission capacity between EU regions, or by reducing the assumed technology improvements.

(Agora Energiewende, 2017) produces cost-optimized power systems for Germany, and tests the sensitivities of their total costs to the cost of PV, batteries, or power-to-gas technologies. It also tests the sensitivity of the production mix to carbon price and to fuel prices.

b. Sensitivity analyses are a way to explore uncertainty and to analyze risks associated with a pathway

Sensitivity analyses are an efficient way to explore uncertainties: when an important exogenous variable is known to be uncertain, exploring a possible range of values for this variable is crucial (IDDRI, 2013).

If results do not change significantly when an important, uncertain variable varies, the scenario is said to be robust to this uncertainty. On the contrary, for some variations, large changes in the results may happen, revealing critical conditions for the original pathway to happen.

For example, if a scenario assumes a significant sobriety effort enabling the implementation of a decarbonized power mix without any decrease in security of supply, testing the sensitivity of the mix when the sobriety effort is not completely achieved is useful. It provides insights on the robustness of the trajectory vis-à-vis CO_2 emissions and answers the question: what impacts of not achieving the sobriety effort? And thus: how important is it to reduce the risk of the sobriety effort not happening?

Sensitivity analyses can thus reveal threshold effects and non linearities. They help decision makers to understand what particular efforts must be made to ensure the adequate conditions for the transition to be successful, or, equivalently, what risks are taken by society when engaging in a given pathway.

c. As any other scenario, a sensitivity analysis is internally consistent

Sensitivity analyses are scenarios which are derived from a main scenario. In this respect, some important points about scenarios are the same about sensitivity analyses:

- The choice of the results to present. Presenting the results of a sensitivity analysis should not be as lengthy as presenting the results of a scenario. The significant differences with the main scenario should be highlighted. Non-linearities / counter-intuitive effects can also be mentioned.
- The inner consistency of the analysis. Modifying an exogenous parameter might be equivalent to modifying a part of the storyline of the scenario. In this case, the storyline as a whole might become inconsistent. In a way, some scenario analyses might be discarded because they would not be considered as credible stories, or at least they should modify other exogenous variables to become credible. For example, a study may perform a sensitivity analysis on the cost of some electricity production technologies. If the costs are much higher in the sensitivity analysis, the overall electricity price may be higher, leading to elasticity effects on the electricity demand. Hence it might not be consistent to assume that electricity demand is the same as in the main scenario in this case.

d. Qualitative sensitivity analyses and transparency on risks associated with a scenario are important tools for scenario community building

Sensitivity analyses are sometimes qualitative: in this case, the scenario producer exposes a qualitative analysis showing what would happen in the scenario with a different hypothesis. This analysis can be completed with a back-of-the-envelope computation ((ECF, 2010) performs such analyses in complement to their quantitative analyses). Qualitative sensitivity analyses rely on the expertise of the scenario producer and on the good knowledge of the model she uses.

Their advantage is their low cost compared to buying expensive modelling time.

Such analyses are useful (at least more useful than no analysis at all) if the hypotheses and the mechanisms leading to the exposed results are explicated. Indeed, more than quantitative analyses, they bring some new questions, can lead to new studies, and they trigger discussion about the model. (ECF, 2010) performs a qualitative "Delivery risk analysis" depicting the variations in the important variables which would lead to negative impacts compared to the main scenarios. This is a useful basis for a better understanding of the scenarios and their limitations as well as for discussion.

Recommendations for scenario producers

A strategy about uncertainty exploration should be defined and justified (with regards to the driving questions). It should include considerations on the decision to perform uncertainty exploration or not. The different aspects of the exploration which are considered should be reported and their links to the driving questions should be outlined. Usually, this exploration is performed through sensitivity analyses. A sensitivity analysis should not modify too many exogenous variables, as its goal is to investigate a particular uncertainty compared to a given scenario (modifying too many exogenous variables is equivalent to designing a new scenario).

Hereunder are aspects of uncertainty exploration which may be reported about:

- Key uncertainties which might affect the scenario, and among them which ones are explicitly explored in the study (Cao et al., 2016). By key uncertainty, we mean a variable which may have important consequences on the overall pathway. Such variables might be detected during the interpretation of previous results[32].

- Qualitative or quantitative nature of the analysis. Qualitative analyzes are useful for scenario community building. They should include a (qualitative) description of the hypotheses and the mechanisms leading to the results. Quantitative sensitivity analyzes should include a (qualitative and/or quantitative) description of the hypotheses and the mechanisms leading to the results.
- Alternative pathways for uncertain exogenous variables which are tested in sensitivity analyses. *For example, energy, or power demand level, key technologies costs and development, delay in action (studying the effect of implementing the transition later), discount rates for simulated agents, social acceptance issues (for example, constraints on where to install new renewables power plants), import prices, demand flexibility, renewables potential (resource quantity, exploitable RES potential, etc.)*
- Key results to present. Presenting the results of a sensitivity analysis should not be as lengthy as presenting the results of a scenario. The significant differences with the main scenario should be highlighted. Non-linearities / counter-intuitive effects can also be mentioned.
- The inner consistency of the analysis. Modifying an exogenous parameter might be equivalent to modifying a part of the storyline of the scenario. In this case, the storyline as a whole might become inconsistent. Some sensitivity analyses might be discarded because they would not be considered as credible stories, or at least they should modify other exogenous variables to become credible.

2. Robustness by storyline

Some scenarios can be designed so as to naturally reduce uncertainty and risks.

For example, a pathway could be designed so as not to depend on future technology breakthroughs: "[Pathways] are based on technologies that are commercially available or in late-stage development today; breakthroughs in technology will only improve the cost or feasibility of the pathways" (ECF, 2010). By taking the most conservative case in which no significant technological improvement happens, uncertainty about technological improvement is tackled.

Similarly, a scenario might consider no power exchange happens with the neighboring regions. This is actually the most conservative case because the possibility of power exchanges can only make the power balance easier to achieve (assuming power sovereignty of the considered region). This strategy is adopted by (ECF, 2010) at the EU level and by (Association négaWatt, 2014; Association négaWatt, 2017) for France.

Another way to tackle risk is to allocate it on several sources (CEDD, 2013), assuming these sources have no common cause[33]. For example, (ECF, 2010) deliberately assumes diversified power mixes even at the expense of sub-optimality: "This approach adds to the robustness of the conclusions; if one technology fails to deliver as expected, the system still works."

Recommendations for scenario producers

Strategies to make storylines more robust should be reported about and explained. *How does the choice of storyline enable an efficient management of uncertainty?*

[32] For linear optimization models, the use of dual variables helps detecting the variables which have the greatest impacts on the results (ADEME, 2015).

[33] In other words, no single cause can make the risks materialize altogether at the same time.

E. A summary of the study strategy steps and how they define the study main dashboard

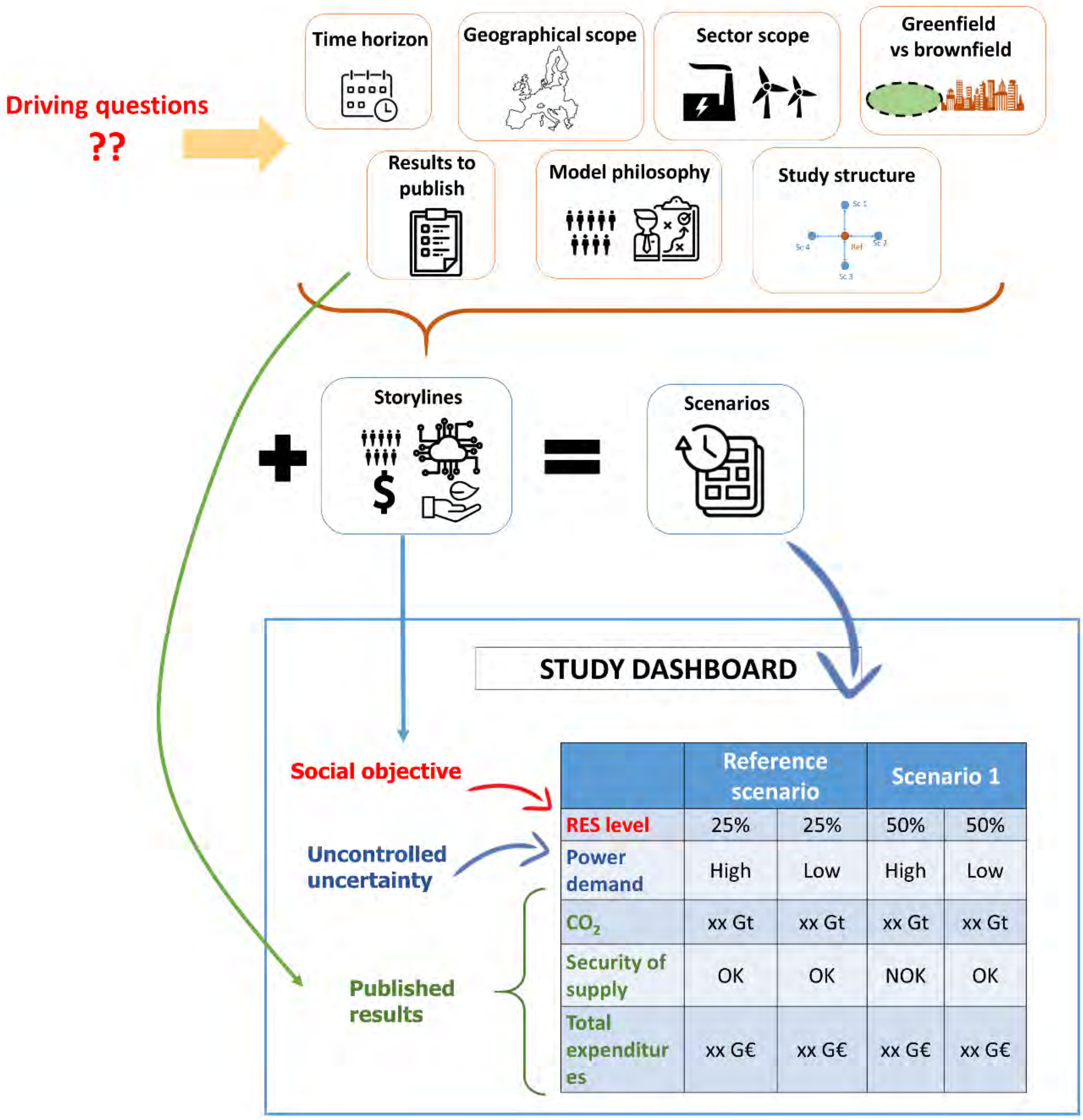

Figure 12 : The study strategy steps and how the main study dashboard is defined from them

The main dashboard of a study compares the different scenarios along key dimensions. These dimensions are (a) the variable parameters which differentiate the scenarios (levers, social objectives and uncontrollable uncertainties) and (b) the published results, which are the endogenous variables that the scenario producer deem useful to compare the scenarios between them.

This dashboard is naturally derived from the study strategy steps (see Figure 12).

III. Results interpretation and publication as a connection to stakeholders to foster debate about the energy transition

A. The crucial and subjective choice of which results to publish

The choice of what to talk about and which results to publish is crucial.

The endogenous variables (that is, those computed by the model) which are selected for publication are compared between scenarios so the reader can assess the value of each scenario along those variables. Not all the variables can be presented because readers (including policy makers) have little time to grasp the insights of the study. Hence a choice on what to present has to be made. For example: how much less CO2 emissions does scenario 1 produce compared to the reference scenario? This choice of variable might be made explicit directly within the driving question. It is a subjective choice as it reflects the scenario producer's vision of what is important to look at for a society and what is not.

The endogenous variables which will be considered as important results to communicate are called in our framework *published results* (see Figure 7). For example the share of RES in the power system, CO2 emissions, land use, GDP evolution, and employment evolutions might be deemed important to communicate and hence published.

Published results can be extremely various. They are the description of aspects of systems included in the future study sector scope (see Figure 1). Hence they can relate to the description of the energy system (for example, a description of the power supply mix), or to the description of the socioeconomic system (for example, the evolution of GDP, employment, etc, or the evolution of the ways of lives), or to the description of the environment (for example CO2 emissions, or lithium depletion).

Published results can be of two types: results about the evolution of the *core system* (that is, the physical components of the energy, or power, system and the way they operate, such as the grid evolution, the power mix in terms of energy and capacity, and so on), and results about the evolution of the surrounding systems.

B. Impact assessment as a narrative about the interactions between the energy transition and the surrounding systems

While the first category of results (about the evolution of the core system) is considered as the description of the energy system (or power system) transition, the second category of results (results about the evolution of the surrounding systems) is often called "impacts", and their computation is often called "impact assessment".

Note that the term *impact assessment* depicts a specific one-way vision of driving forces within models. Studies talk about *impacts* when they consider the transition of the core system has an effect on some variables, but not the other way round. For example, it is often considered in future studies that the energy transition alters CO2 emission, but that CO2 emissions have no impact on the energy transition. This is a simplification of reality as CO2 emissions lead to a climate change which in turn increases the so-called "physical risks". These risks correspond to impacts on the economy and in particular on the core system transition. In other words, the term impact derives from models in which environmental, social, and (for some of them) economic systems do not loop back on the energy system.

Hence in the present framework, we will sometimes talk about *interactions with surrounding systems* instead of *impacts*. These interactions include interactions with the economic system, society, and the environment (see Figure). They could also be called "co-evolution of surrounding systems."

Impact assessment fundamentally is about telling the story of how systems surrounding the energy system (such as the environment, society, or the economy) evolve during the proposed energy transition, due to the activities taking place within a given geographical and/or sectoral perimeter (see section on impact assessment).

C. Impact assessments are the most concrete and useful links between the proposed energy transitions and society in a broad sense

The choice of which result to publish is important because of communication efficiency. But the choice of which interaction with surrounding systems to talk about is even more important because interactions connect the scenario more directly with broader parts of society than results about the sole technical energy system.

The evolution of surrounding systems such as the environment, ways of lives, or the economy highly interest citizens, households, and various economic agents and policy makers, whereas the evolution of the technical energy system per semainly interests energy systems' economic agents and policy makers in the field of energy. For example:

- Interactions with the environment interest parts of civil society; among those interaction, interactions with the atmosphere through GHG emissions interest a growing part of local and national policy makers.
- Interactions with the economic system (costs, financing efforts, energy security of supply, energy price…) potentially interests many corporations for their strategies' designs, and many policy makers.
- Interactions with society (behavior changes, desirability of the transition, quality and security of supply) interest households and citizens.

In this sense, the transitions proposed in studies are mostly judged through the lens of these interactions. Hence the choice of which impact to present is key.

This choice evidently depends on the target audience. Most audience now consider that climate impacts should be measured, and new topics are on the raise, such as impacts on biodiversity, or on mineral resources.

More practically, the choice also depends on current modeling capacity[34].

The choice may also be critical because a given impact may be a strong driver of the scenario design. Evidently, a scenario which does not care about GHG emissions radically differs from a scenario seeking to strongly reduce GHG emissions. Similarly, taking into account aspects of biodiversity impacts, or the desirability of transitions, could lead to radically different scenarios.

A. Impacts are better communicated through one narrative for each impact rather than through integrated, opaque values such as extended cost indicators

As impact assessments (whether supported by indicators or not) are the most concrete depictions of the consequences of an energy transition for individuals, companies, decision-makers etc., these narratives (or the associated key indicators if any) are much more efficiently communicated separately and synthesized through a multi-criteria dashboard, rather than through an integrated value such as an "extended cost" integrating externalities. Such narratives enable a more transparent and informed debate about the energy transition.

One of the main goals of the present framework, through its thematic sections, is to foster the emergence of concrete enough depictions of the proposed pathways so that their different impacts on society, the economy, employment, or environment can be easily discussed among policy-makers.

Some studies present costs as a key indicator by integrating a carbon price in their results (Agora Energiewende, 2017; Fraunhofer ISE, 2015). Some other rather present a dashboard of various indicators to compare the proposed scenarios (ADEME / Artelys, 2018; ANCRE, 2013; European Commission, 2011; The Shift Project, Kahraman, Guérin, & Jancovici, 2017).

It is now commonly acknowledged that cost, as a single value (a scalar value), does not, and cannot be a proxy for all the aspects of an energy transition:

[34] As of today, models computing impacts on mineral resources are just emerging (ADEME/IFPEN, 2018; Calvo, Valero, & Valero, 2017; Valero et al., 2018) so future studies considering this aspect are still scarce.

- It does not because prices do not include externalities (by definition of an externality: an impact which is not represented in price, e.g. pollution), and the list of all externalities (positive or negative) is not known and cannot be completely known.
- It cannot because the impacts of an energy transition are so various that it would require to perfectly know the world to assess the values of all the externalities and integrate them into a useful indicator. For example, it would take a perfect knowledge of biodiversity trophic and interaction networks to give a value for a transition on this subject. This complex system might never be sufficiently understood conceptually speaking (lack of knowledge about the complex interactions between species), and never be monitored precisely enough (lack of knowledge about initial situation, also known as chaos theory limit) to confidently assess interactions between them and the proposed energy system transition.

Perfectly evaluating a transition scenario through a unique global cost indicator may not even make sense in democracies. Indeed, what would ensure the legitimacy of such an undebatable indicator?

B. For future studies, a description should not be considered as precise if it is not concrete enough to be debated by stakeholders

When comparing transitions together, all the significant interactions with surrounding systems have to be considered before decision-making about which pathway to choose. Forgetting one significant interaction (for example, with ways of lives) may lead to unexpected negative outcomes.

Some impacts might be deemed unacceptable for a given society. The role of a scenario is to disclose those impacts under a concrete and intelligible form for those who will undergo those impacts. The goal of asking scenario reports to assess concretely enough the impacts of the energy transition they propose and to be transparent about them is to inform as best as possible the debate about energy systems transition so that later, people do not feel they have been deceived.

A useful and efficient description is concrete enough to be debated among stakeholders

We call *concrete description* of an assessment a description which is precise enough (in qualitative terms) for an interested stakeholder to understand what it concretely means for her and for society, so that she can intelligently discuss it. For example, ways of lives can be precisely described (under the form of different narratives) so that individuals can concretely imagine the world which is described from their current situation. A concrete description can be based on figures produced by the model or be at the origin of figures that are inputs to the model. In any case, the concrete description is consistent with those figures.

Making a description more concrete may require to pose more hypotheses, to collect more data or to perform more calculations. E.g. telling that the use of lightbulbs will decrease by 10 % does not tell much about how it will materialize in the lives of households or companies. Saying that people will always shut off the light when they are not in a room is a deeper description even though it may correspond to the exact same reduction. However, in order to deduce that 10 % of the use will be avoided thanks to the different behaviors of people, the scenario producer needs to collect data about the actual use of lighting, or to directly pose this assumption.

The concreteness of a description depends on the target audience, as is illustrated by this example about climate change: saying that average temperature would increase by 2.3°C by 2050 compared to pre-industrial era in a scenario may be a concrete enough description for some decision makers, but may not be concrete enough for the greater public (the layperson may not concretely understand what such an increase would mean for her and for society).

If, during the scenario production process, such an unacceptable impact seems to emerge, the scenario can be reworked by modifying some assumptions. On the long run, the *concrete description* of interactions with surrounding systems makes future studies stronger and more useful for society.

In practice, two approaches can be used to produce scenarios avoiding unacceptable impacts: either the impact is assumed to remain within acceptable bounds beforehand (ex-ante) in the scenario (as a backcasted component), or the impact is measured ex-post (after running a model) and only scenarios in which the impact remains within acceptable bounds are kept in the final report (Schubert, Thuß, & Möst, 2015). Typically, CO2 emissions are assumed beforehand to decrease below a given level in transformational scenarios, whereas acceptability issues are generally assessed ex-post.

Fostering transparency trough concrete descriptions of impacts is a critical objective of this framework.

Recommendations to scenario producers

Specifically, the list of the published results may be provided and justified. A list of important subjects (according to scenario and power systems' experts) is provided by the present framework, and can be used as a reference. *For example, why are CO_2 emissions considered as an important result to publish? Why is power distribution grid evolution not described? Why are electrical appliance stock evolution not described? Why is biosphere integrity not considered?*

Scenario producers should detail their strategy about results publication, especially interactions with surrounding systems justified (with regards to the driving questions, to modeling constraints, to ethical considerations, etc). The following aspects should be considered:

- Nature of the published results and interactions which are studied: *what interactions will be considered in the study? What results will be published?*
- Reasons for these choices. Scenario producers should explain why these interactions have been selected, and why other interactions (especially the ones which will be described in this framework) have not been considered. *Why is job evolution not considered in the scenario? Why are material resources not considered in the scenario? why are CO_2 emissions considered as an important result to publish? Why is power distribution grid evolution not described? Why are electrical appliance stock evolution not described? Why is biosphere integrity not considered?*
- For the interactions which are not studied, scenario producers should provide an analysis (even short and qualitative) considering the possible effects on the scenario of including this aspect in the scenario.

Scenario producers should provide concrete descriptions of the evolution of the surrounding systems (climate, resources, economy, ways of lives and so on) they chose to deal with.

These considerations also apply to the reference/BAU scenarios of studies.

C. Internal inconsistencies can be revealed through a consistency check between the storyline and its impacts

The storyline is the physico-socio-political context in which the energy system evolves. The storyline is theoretically internally consistent all along the scenario timeframe. However, the consequences of a storyline might actually be inconsistent with the storyline itself; for example, a constant, world growth hypothesis might contradict the physical availability of petroleum. As many information are delivered by models, it is important to check that the consequences of the storyline do not question the storyline itself, or the whole scenario would be inconsistent.

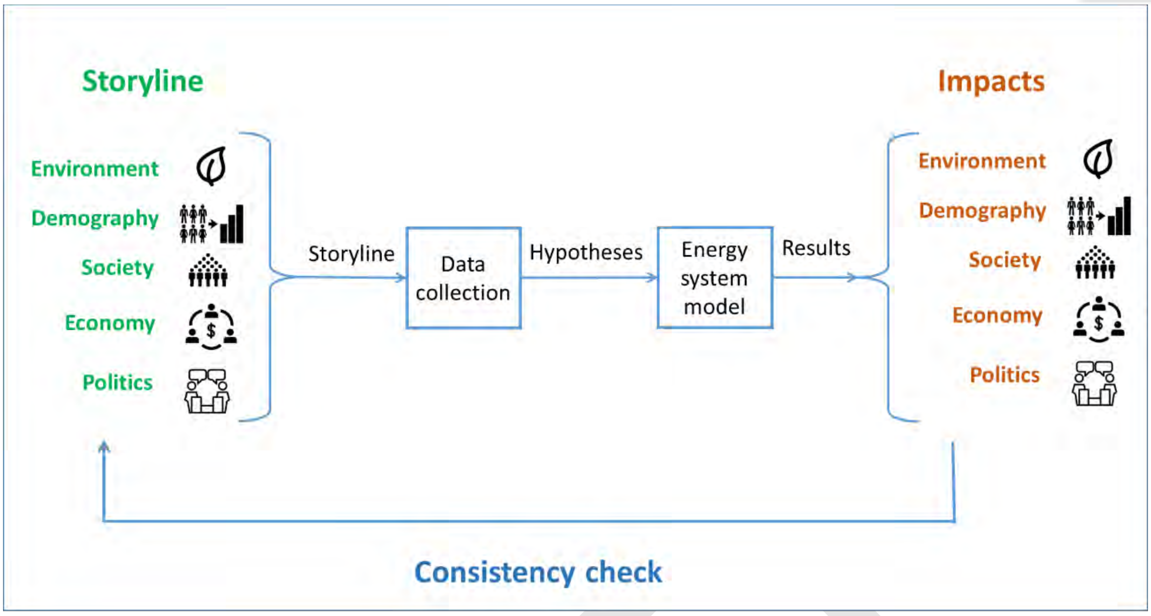

Figure 13: The storyline is at the origin of the input variables which feed the model, producing in turn results and insight about the various consequences of the initial storyline. As long as there is no modeled feedback between these impacts and the energy system, a manual check has to be performed that the impacts are not inconsistent with the initial storyline.

Another example is typically found in Reference, or so-called Business As Usual (BAU) scenarios. These scenarios do not usually seriously tackle the climate change challenge. However, these scenarios do not take into account the impacts of an important climate change by 2050 (2040 for the World Energy Outlook) and do not provide a substantiation for this (ECF, 2010; European Commission, 2011; European Commission, 2016; OECD/IEA, 2017).

However, some serious impacts of such a climate change can be expected, such as large migratory flows between countries, realistically impacting world economies. From this we can conclude that many of these scenarios are not internally consistent without mentioning it.

Secretly inconsistent scenarios (that is, scenarios which are inconsistent without being clear about it) may harm decision-making process by hiding important information. However, openly inconsistent scenarios can be useful within the energy transition debate. For example, it is useful to know that a pathway does not model the impacts of climate change within the scenario while being clear that it is not realistic and explaining what the impacts would be.

Concrete descriptions of impacts would very directly shed light on such inconsistencies. Their concrete descriptions over the scenario timeframe and beyond (because the climate system has a large inertia, a significant share of the impacts happen after the end date of scenarios) would also directly show the unacceptable nature of these consequences.

Recommendations to scenario producers

Studies reports should check for inconsistencies within their scenarios, report and substantiate them if any (*why was it decided to publish an inconsistent scenario?*) and provide an analysis (qualitative or quantitative) of what the scenario would look like if the inconsistency was solved (*what would be different within the consistent version of the scenario compared to the published one?*).

Bibliography

ADEME. (2012). *L'exercice de prospective de l'ADEME - « Vision 2030-2050 ».*

ADEME. (2013). *L'évaluation macroéconomique des visions énergétiques 2030-2050 de l'ADEME - Document technique*. Consulté à l'adresse https://www.ademe.fr/evaluation-macroeconomique-visions-energetiques-2030-2050-lademe-l

ADEME. (2014). *Visions énergie climat 2030/2050 - Quels modes de vie pour demain ?* (Nº 8102; p. 132).

ADEME. (2015). *Un mix électrique 100% renouvelable ? Analyses et optimisations*.

ADEME. (2017). *Actualisation du scénario énergie-climat ADEME 2035-2050*.

ADEME / Artelys. (2018). *Trajectoires d'évolution du mix électrique 2020-2060 - Synthèse*.

ADEME/IFPEN. (2018). *Electrification du parc automobile mondial et criticité du lithium à l'horizon 2050* (p. 73).

Agora Energiewende. (2015). *The Integration Costs of Wind and Solar Power*.

Agora Energiewende. (2017). *Renewables versus fossil fuels – comparing the costs of electricity systems*.

Agora Energiewende, IDDRI. (2018). *L'Energiewende et la transition énergétique à l'horizon 2030*.

ANCRE. (2013). *Scénarios de l'ANCRE pour la transition énergétique*.

Association négaWatt. (2014). *Scénario négaWatt 2011-2050 - Hypothèses et méthode*.

Association négaWatt. (2017). *Scénario négaWatt 2017-2050 | Dossier de synthèse* (p. 48).

Bovari, E., Giraud, G., & Mc Isaac, F. (2018). Coping With Collapse: A Stock-Flow Consistent Monetary Macrodynamics of Global Warming. *Ecological Economics*, *147*, 383-398. https://doi.org/10.1016/j.ecolecon.2018.01.034

Briand, Y., Bataille, C., & Waisman, H. (2018). *How to structure the public debate on the low-carbon future of passenger transport?* 4.

Callonec, G., Landa Rivera, G., Malliet, P., Saussay, A., & Reynès, F. (2016). Les propriétés dynamiques et de long terme du modèle ThreeME. Un cahier de variantes. *Revue de l'OFCE*, *5*(149), 47-99.

Calvo, G., Valero, A., & Valero, A. (2017). Assessing maximum production peak and resource availability of non-fuel mineral resources: Analyzing the influence of extractable global resources. *Resources, Conservation and Recycling*, *125*, 208-217. https://doi.org/10.1016/j.resconrec.2017.06.009

Cao, K.-K., Cebulla, F., Gómez Vilchez, J. J., Mousavi, B., & Prehofer, S. (2016). Raising awareness in model-based energy scenario studies—a transparency checklist. *Energy, Sustainability and Society*, *6*(1). https://doi.org/10.1186/s13705-016-0090-z

Capros, P. (s. d.). *Primes Energy System Model*. E3M Lab - National Technical University of Athens.

Carbone 4. (2014). *Etude des 4 trajectoires du DNTE*.

Carpos, P., Paroussos, L., Fragkos, P., Tsani, S., Boitier, B., Wagner, F., … Bollen, J. (2013). Description of models and scenarios used to assess European decarbonisation pathways. *Energy Strategy Reviews*, *2*(3/4), 220-230.

CEDD. (2013). *L'évaluation économique des scénarios énergétiques*.

Centre d'analyse stratégique. (2012). *Rapport énergies 2050*.

CGDD. (2016). *Trajectoires de transition bas carbone en France au moindre coût*.

Child, M., Koskinen, O., Linnanen, L., & Breyer, C. (2018). Sustainability guardrails for energy scenarios of the global energy transition. *Renewable and Sustainable Energy Reviews*, *91*, 321-334. https://doi.org/10.1016/j.rser.2018.03.079

CIRED, RAC-F. (2012). *Building a low-carbon scenario for France - How a participatory approach can enhance social and economic acceptability*.

Donella H. Meadows, Randers, J., & Meadows, D. L. (2004). *Limits to growth: The 30-Year Update*. Chelsea Green Publishing; 3 edition (June 1, 2004).

Dreborg, K. H. (1996). Essence of backcasting. *Futures*, *28*(9).

ECF. (2010). *Roadmap 2050 - A Practical Guide to a Posperous, Low-Carbon Europe*.

European Commission. (2011). *Energy Roadmap 2050 - Impact assessment and scenario analysis*.

European Commission. (2016). *EU reference scenario 2016: energy, transport and GHG emissions : trends to 2050.* Luxembourg.

France Stratégie. (2017). *Discount rate in project analysis*.

Fraunhofer ISE. (2015). *What will the energy transformation cost? - Pathways for transforming the German energy system by 2050*.

Greenpeace. (2015). *Energy [R]evolution - A sustainable world energy outlook 2015* (p. 364).

Guivarch, C., Lempert, R., & Trutnevyte, E. (2017). Scenario techniques for energy and environmental research: An overview of recent developments to broaden the capacity to deal with complexity and uncertainty. *Environmental Modelling & Software*, *97*, 201-210. https://doi.org/10.1016/j.envsoft.2017.07.017

Hache, E., & Palle, A. (2018). *Intégration des énergies renouvelables variables dans le système électrique : analyse bibliométrique et enquêtes auprès des acteurs*. 18.

Hache, E., & Palle, A. (2019). Renewable energy source integration into power networks, research trends and policy implications: A bibliometric and research actors survey analysis. *Energy Policy*, *124*, 23-35. https://doi.org/10.1016/j.enpol.2018.09.036

IDDRI. (2013). *Scénarios de transition énergétique pour la France : définir un espace de discussion pour le débat* (p. 16).

IIASA. (2012). Energy Pathways for Sustainable Development. In *Global Energy Assessment Towards a Sustainable Future*.

Imperial College London, NERA, DNV GL. (2014). *Integration of Renewable Energy in Europe* (Nº 9011-700).

Joint Research Center. (2015). *JRC Data Policy* (Nº JRC95307).

Lappeenranta University of Technology / Energy Watch Group. (2017). *Global energy system based on 100% renewable energy - Power sector*.

Mark Elsberg. (2017). *Blackout. Tomorrow will be too late*. Sourcebooks Landmark.

OECD/IEA. (2017). *World Energy Outlook 2017* (p. 782).

RTE. (2017). *Bilan prévisionnel de l'équilibre offre-demande d'électricité en France*.

Schubert, D. K. J., Thuß, S., & Möst, D. (2015). Does political and social feasibility matter in energy scenarios? *Energy Research & Social Science*, *7*, 43-54. https://doi.org/10.1016/j.erss.2015.03.003

SFEN. (2018). *Le nucléaire français dans le système énergétique européen*.

SLC. (2017). *Diviser par quatre les rejets de CO2 dus à l'énergie : Le scénario Négatep 2017*.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., … Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223), 1259855. https://doi.org/10.1126/science.1259855

The Shift Project, Kahraman, Z., Guérin, A.-J., & Jancovici, J.-M. (2017). *Décarbonnons ! 9 propositions pour que l'Europe change d'ère*. Odile Jacob.

Valero, A., Valero, A., Calvo, G., Ortego, A., Ascaso, S., & Palacios, J.-L. (2018). Global material requirements for the energy transition. An exergy flow analysis of decarbonisation pathways. *Energy*, *159*, 1175-1184. https://doi.org/10.1016/j.energy.2018.06.149

World Bank. (2009). *Climate Change and the Economics of Targeted Mitigation in Sectors with Long-Lived Capital Stock*.

World Energy Council. (2016). *World Energy Scenarios | 2016*.

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The Shift Project

The Shift Project, a non-profit organization, is a French think-tank dedicated to informing and influencing the debate on energy transition in Europe. The Shift Project is supported by European companies that want to make the energy transition their strategic priority & by French public funding.

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Energy transition models

Technical file #2 – Draft version

Information and recommendations for scenario producers

This document is part of a set of 12 technical files. These files have been produced by *The Shift Project* after one year and a half of research and experts consultations on the different aspects of energy transition and the future studies around these aspects.

Our project, "Power Systems 2050 – Guidelines for design," started in January 2018, with the participation of 10 experts who defined the key subjects which according to them have to be collectively tackled by future studies about the power transition. *The Shift Project* then investigated each of these subjects, consulting in total 40 experts, organizing 4 workshops, and reviewing a large bibliography, including a dozen of future studies about power (and energy) transition at different geographical scales.

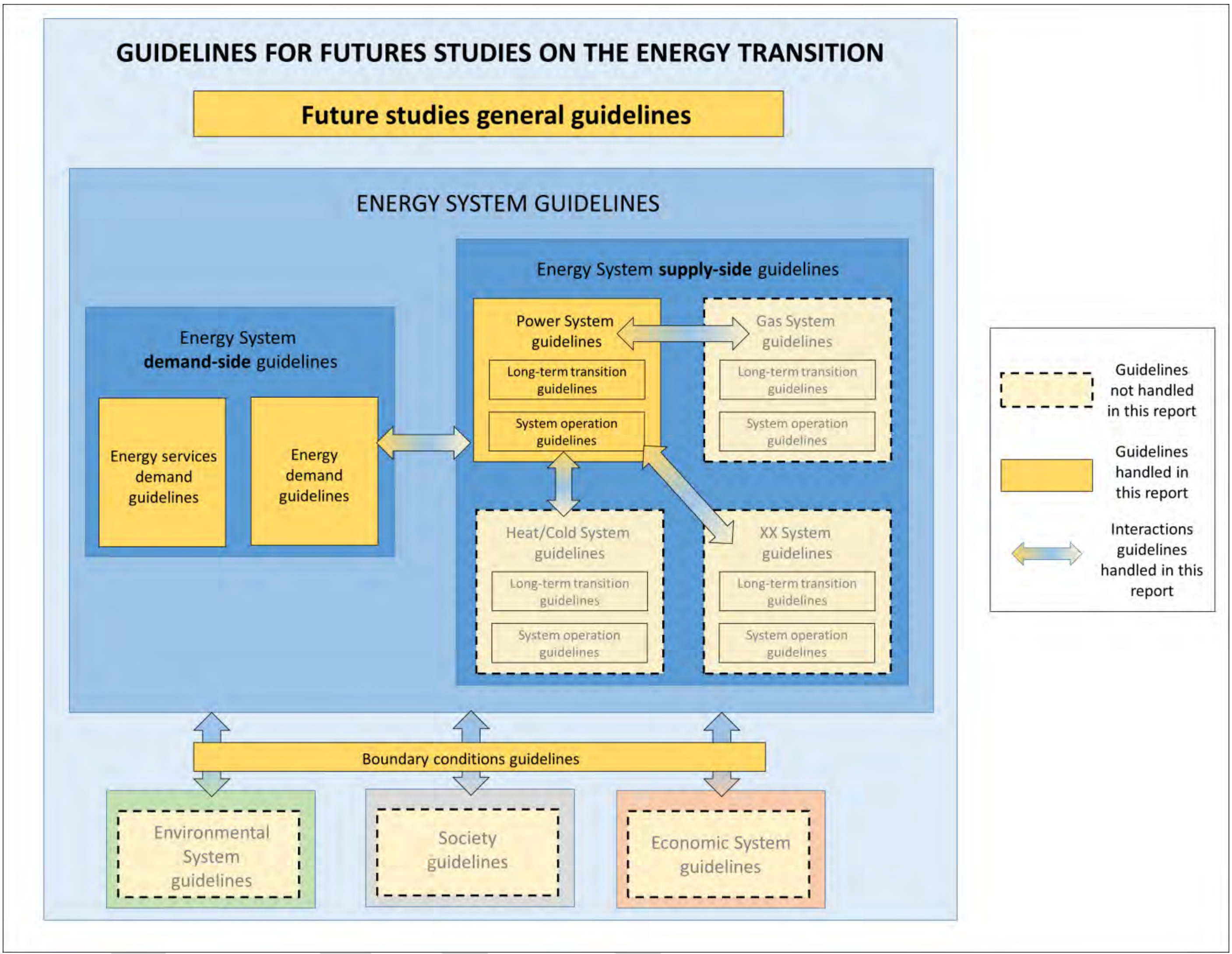
The goal of this project is to produce a set of guidelines addressed to scenario producers. These guidelines seek to foster transparency and consistency *within* future studies and to develop a common language *across* studies. By defining a number of important items which are key to deal with in future studies, we actually propose a study template which enables a better understanding of the location of each proposed scenario on the tree of possible transitions. Once again, the objective is not to *rank* studies, or scenarios, but rather to *compare* them to get a better collective overview of the different aspects of the transition (what are the differences between studies in terms of driving questions, hypotheses, models, methodology, results?).

Several aspects of the energy transition are handled in these technical files. However, on the energy supply-side only the power system has been studied. The main reason for this choice is that we had to start from somewhere with limited resources, and the power system seemed to be a key system to study in the energy transition context, towards a low-carbon economy, as shown by the growing number of future studies focusing on this system. However, the guidelines we propose could be completed by analyzes on the other energy supply-side systems (the gas system, oil system, heat system and so on).

Each technical file tackles several aspects of future studies for the power (and energy) transition. Here is the complete list of the technical files produced during the project:

#	Technical file title
1	Future studies on the energy transition
2	Energy transition models
3	Boundary conditions for energy transition scenarios
4	Long-term evolution of energy consumption in energy transition scenarios
5	Lifestyles and consumption behaviors in energy transition scenarios
6	Long-term evolution of the power system supply-side in energy transition scenarios
7	Power system operation in energy transition scenarios
8	Impact assessment in energy transition scenarios
9	Transition desirability in energy transition scenarios
10	Environmental assessment of energy transition scenarios
11	Economic evaluation of energy transition scenarios
12	Employment assessment of energy transition scenarios

Altogether, these files cover the fields described on the following map of the guidelines for future studies on the energy transition. The document you are reading covers a cross-cutting topic, hence it may be linked to all the topics.



In addition to these technical files, three complementary notes have been produced as specific focuses on the following aspects: material criticality in energy transitions (in French, to be translated and added to technical file #10), levelized cost of electricity (LCOE) in energy transition future studies (in French) and discount rate in energy transition future studies (in French).

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Table of content

Reading keys

Explanation box, containing key information for a better overall understanding of the subjects.

Recommendations to scenario producers:

These boxes contain the recommendations for scenario producers.

The word "should" means that scenario producers, if they are to follow the guidelines, must substantiate the corresponding point. The words "may" or "might" relates to suggestions, ideas to help the scenario producer respond to the point.

Questions in italic are examples of questions scenario producers might ask to substantiate the points. They are here in an illustration purpose.

Phrases in italic relate words which are being defined and will be subsequently used in the framework.

I. Making models understandable

Scenarists are confronted with a wide diversity of models, and scenario readers may misunderstand the role, the assumptions and the limitations of each one. Making models understandable for scenario readers is key to improve trust in future studies.

A. A model is a simplified representation of a real system

A model is a simplified representation of a real system and of the phenomena that occur within it. This description and the parameters it includes derive from theoretical or empirical basis and aim to answer a question.

An energy model is a model which focuses on energy issues. It uses and combines data from different sources to describe the energy system such as energy demand and supply, by determining invariable parameters[1] describing *interactions* between *modeled entities*. Modeled entities are the concepts, objects and actors that the modeler represented in the model. Usually interactions between them are described as equations whose parameters are fixed for all the scenarios of the study. Sometimes they are defined as non-parametric[2] interaction rules. Energy models are used as tools for generating consistent scenarios in future studies about the energy transition (See section on studies). They use inputs (variable parameters[3]) and produce useful outputs (published results[4]) to answer the driving questions of the study.

B. Modeling the energy system is an extremely complex work

Modeling activities may be performed by companies, or university laboratories, specialized in energy system, environment and macro-economic modeling. These entities use their in-house models which can be tuned to the specific questions and data brought by scenario producers after their study strategy activities. For example, the European Commission designed scenarios and then contracted the National Technical University of Athens to model scenarios (PRIMES model was used (European Commission, 2011)).

Intense interaction happens between scenario producers and modelers, when they are not the same teams. Scenario-producers might monitor the modeling activities in order to ensure the model is properly tuned and the variable hypotheses can be integrated into the model, or just trust the modelers depending on the modeling experience of the scenario producers. When scenario producers have modeling skills they might even challenge modelers to find the best modeling solution[5]. When they do not, modelers might explain to them as clearly as possible the options and limitations of their models. They might also clearly phrase the driving questions their model can (or cannot) answer and work with scenarists to determine if the model can fulfil their modeling needs.

Scenario producers may design and implement pre- and post-processing modules to adapt inputs to the model from raw data and to adapt model's outputs to the interpretation and publication of results.

In other cases the same team, or person, performs scenario design and modeling activities (for example associations such as negaWatt or Negatep in France). Big agencies such as IEA or companies such as RTE developed their own models (the World Energy Model and the ETP model for EIA and the open source model Antares[6] for RTE).

Modeling activities consist in designing and producing a model, or tuning an already existing one, able to fulfill the needs of a future study. The tuning might be the activation of an option already implemented in the model, or the production of a new module in the model. For illustration purpose, we take the question "What would be the implications of reaching a fourfold decrease of CO_2 emissions in France with more RES, energy sobriety and energy

[1] See section on future studies
[2] That is, not described as equations (for example, they can be described as logic gates).
[3] See section on future studies
[4] Ibid.
[5] A model able to answer the driving questions at the lowest cost and before a given deadline.
[6] https://antares.rte-france.com

efficiency, for the environment, the economy, lifestyles, research activities and energy industry activities? [7]". Modeling activities are composed of:

- Defining the *variable parameters*, which will be part of the exogenous variables in the model and whose values will be controlled by scenarists for each scenario. In other words, the model must offer the possibility to adjust a given set of variables. These variables have been described as *levers*, *social objectives* or *uncontrollable uncertainties*[8]. They are determined by the planning question and brought by scenarists. In the example question, RES installed capacity, final energy consumption and consumption devices technology have to be variable parameters in order to investigate their effects.
- Determining the important endogenous variables. They are those variables which are considered as the main *results* to communicate according to the planning question. In the example question, indicators about the environment, economy, lifestyle, research activities and energy industry activities are the important endogenous variables. The model must provide the possibility to extract these indicators.
- Modeling the entities brought into play by the planning question and determining the functional links between them, that is, finding out how these entities interact with each other. The example question requires to define the links between CO_2 emissions and the whole energy system, as well as the links between the energy system and respectively, environment, the economic system, research activities, energy industry activities, and lifestyles. It requires in turn to model the energy system, the environment, etc. This step requires a thorough understanding of the whole economy, energy system, or power system depending on the sector scope of scenarios, and data about the parameters defining these systems and the interactions between their elements. These data are often based on external, research sources. This is why this very complex modeling is sometimes performed by specialized teams, composed of experts from various domains.

Once the model is designed and implemented (usually under the form of a computer algorithm), it is run once per scenario, each time producing a set of results corresponding to a set of different *variable parameters*.

C. Scenario readers should be able to understand a model through the story it tells about how a system works

Understanding how a real system is represented in the model is of interest for scenario users and readers, as opposed to understanding how the modeling tool has been designed and implemented. Similarly, a book reader is interested by the story in the book rather than by how the book has been produced or the material it is made of. In this respect, describing a model efficiently for scenario readers is similar to explaining how the described world operates using usual, real-world, concrete concepts. Hence we consider in this framework that the specific computational methodology, programming technique and mathematical logic of models are not of interest for scenario users and readers whenever they do not tell anything about the world they represent. They are rather a diverse set of tools enabling to represent the same systems in different fashions.

II. Models for dummies: describe the represented entities and their interactions

The purpose of this technical file is to make a clear and transparent link between the selected, or designed, model and the driving questions of the study. Indeed scenario producers usually make sure the model they use is suitable to answer their driving questions.

In this section, we seek to determine key characteristics of models which should be made explicit by scenario producers to have the best chance their readers understand the model they used. In addition, scenario producers need a good understanding of the model they use in order to be sure it can answer their driving questions, especially when they use an off-the-shelf model. We first reviewed models classifications in search for key characteristics.

[7] This planning question is implicitly asked in ANCRE 2013

[8] See section on future studies.

A. Models classifications might not be the right tool to quickly understand complex models

1. **Existing models' classifications are numerous**

Many researchers have made attempts to classify models (Bhattacharyya & Timilsina, 2010; Boulanger & Bréchet, 2003; Connolly, Lund, Mathiesen, & Leahy, 2010; Després, Hadjsaid, Criqui, & Noirot, 2015; Herbst, Toro, Reitze, & Jochem, 2012; van Beeck, 1999) that can be aggregated in the following diagram (see Figure 1).

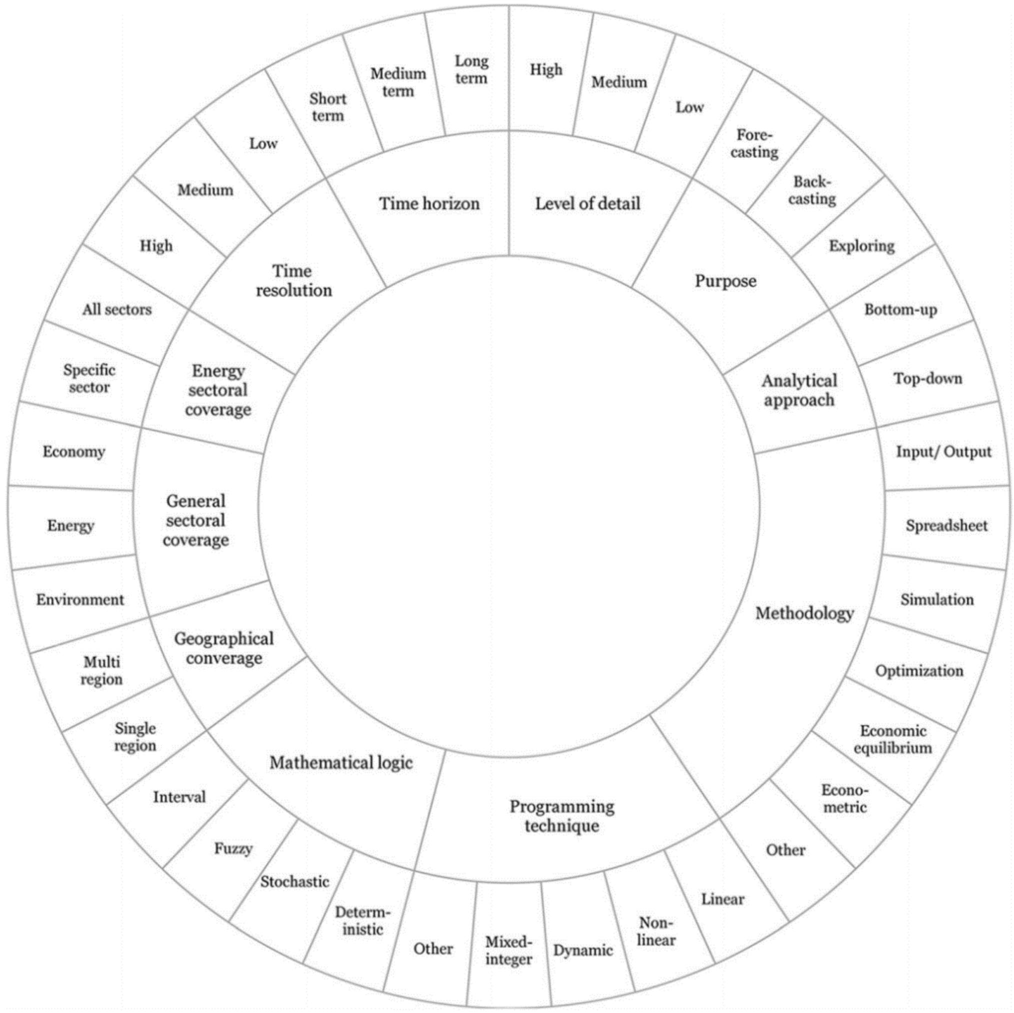


Figure 1 : Classification of models, by (Cao, Cebulla, Gómez Vilchez, Mousavi, & Prehofer, 2016)

Models can be classified by purpose (e.g. to explore the impacts of different levers or to normatively investigate how to achieve social objectives); by analytical approach (i.e. whether technology-based bottom-up, or economy-based top-down); by methodology (e.g. optimization, simulation or equilibrium models); by geographical perimeter (i.e. what regions can be modelled), by level of detail (i.e. the level of aggregation of entities represented in the model); by sectoral perimeter (i.e. modelling the whole economy or only the energy system, or power system); by time horizon and by model time resolution.

2. Scopes of models should be compatible with those of scenarios

Several of the proposed classifications have already been dealt with in the studies section. Indeed, time horizon, geographical coverage, sectoral coverages, and backcasting / exploratory purposes are considered in this framework as characteristics of the study rather than characteristics of the model. In other words, we consider that model design or model selection derive from study design (see figure in studies section).

However this point of view is quite theoretical as in practice strategy design of the study, or even driving questions, are partly model-driven. In other words, the availability of off-the-shelf models may partly determine which questions will be asked by scenario producers, especially when modeling skills, or available resources or time are lacking for the scenario team.

The goal of this section is to provide keys to scenario readers for a better understanding of how a studied system is represented in models, and to provide recommendations for scenario producers to improve this understanding in others.

In this respect, scopes of studies and of models (that is, geographical and sectoral scopes as well as time horizon) do not tell how the system is represented but what parts of it are represented and over which period of time. Of course, the scopes of a study and the scopes of the model used by the study must be compatible (either the scope of the model contains the scope of the study, or the model must be completed with modules, or qualitative considerations to fill the gaps).

In particular, scopes of models usually enclose the published quantitative results of studies, such as energy and/or power supply by assessing its level, its technological forms and/or its costs. In our framework, other outputs are the evolutions of the *surrounding system* in interaction with the energy system such as the impacts on the economy, society, the environment or the security of supply. If results are published about these surrounding systems, most often the associated aspects of surrounding systems are modeled (e.g., some aspects of society, or environment might be modeled). For qualitative results (in particular on aspects which are difficult to quantify such as lifestyles), storytelling approaches might be used in combination to quantitative approaches.

By way of examples, ThreeMe (OFCE) can be used to assess GDP, employment or energy bill (Callonec, Landa Rivera, Malliet, Saussay, & Reynès, 2016), ADEME conducted a study on the interplay between energy transition and lifestyle (ADEME, 2014), and Integrated Assessment Models (IAMs) such as DICE, MERGE, MESSAGE also aim at representing the interaction between the environment and the energy system (Després et al., 2015).

3. Models methodologies (optimization, equilibrium or simulation) inform about how transition agent(s) decide

As (IEA-RETD, 2013) puts it, "Human behavior is enormously complex to model. It may be the most uncertain aspect of our energy future, especially when transformative futures are envisioned". A key aspect to understand models is to understand how decisions driving the transition are taken in it.

Models use optimization, simulation or equilibrium methodologies (IEA-RETD, 2013), according to the way decisions are taken about the energy system evolution.

Optimization methodology is used to represent a world driven by the search of a global optimality, such as a least cost trajectory under some constraints. METIS model (ARTELYS / European Commission, 2017).

Equilibrium methodology is used to represent a world driven by balanced markets. This method assumes a unique price equilibrium exists for each market and assumes that decisions by agents are only driven by profit considerations. To make their decisions, these agents take into account information which is available to them. This information may be a complete and perfect knowledge about the future, or only partial information about the future. This leads to biases towards high inertias for key market actors' behaviors (e.g. how consumers value goods relative to each other are calibrated from historical economic data; similarly, use of capital, labor, energy and material to produce goods are calibrated from historical data). PRIMES model uses such a methodology (E3Modelling, 2018).

Simulation methodology is used to represent a world driven by rules applied step by step, year after year, such as investment decisions across competing technologies or plant commissioning/decommissioning decisions. Such rules can be defined by the scenario producer as to produce macro-behaviors which are similar to those observed today or instead they can be defined so as to produce new, "transformational"[9] behaviors. Compared to equilibrium methodology, the emphasis is on representing a system not purely driven by financial costs and profits. For instance, a technology may capture a share of the market even though its life-cycle cost is higher than that of other technologies (Energy Technology Systems Analysis Programme, 2016). POLES (Keramidas,

[9] Related to high rates of change within the transition, as opposed to "business-as-usual".

Kitous, Schmitz, European Commission, & Joint Research Centre, 2017), or the World Energy Model (International Energy Agency, 2018), use this methodology.

In the section about future studies we introduced the "scenario philosophy" concept. Two philosophies about the *transition agent* which controls the energy system transition in scenarios have been described: simulated agents or benevolent planner. In the first philosophy, the evolution of the energy system is driven by agents whose behaviors are modelled and which pursue different objectives. In the second philosophy, energy system evolution is driven by a benevolent planner who follows rules and knows the global energy system.

The benevolent planner representation of the world uses the optimization methodology when the planner seeks global optimality. However, benevolent planners can use different criteria as optimality. They can instead drive the transition following qualitative rules (such as a nuclear phase-out according to a given roadmap with renewable sources in replacement). In this case, simulation methodology is used.

The simulated agents representation of the world can use the simulation methodology if the modeler wants to represent agents' decisions (for example, investments decisions) in a specific way. Or, the equilibrium methodology can be used if the scenario producers wants to represent agents' decisions as if they were in a balanced market world calibrated on today's markets. Some studies implement financing agents whose foresight is perfect; in other words, these agents have a perfect information of all the other agents' behaviors, past of future. These extreme hypotheses produce a cost-optimal emergent behavior for the energy system. In other words, this modeling is equivalent to a cost-optimization by a benevolent planner.

Transition agent	Model methodology		
	Equilibrium	Optimization	Simulation
Simulated agents	Agents act in balanced market similar to today's one	Agents act with a perfect foresight: equivalent to benevolent planner cost-optimization	Agents control the long term transition following individual specific rules
Benevolent planner	N/A	Benevolent planner seeks to optimize the system as a whole along defined dimensions and under some constraints	Benevolent planner controls the long term transition following system-wide rules

Hence the methodologies can be seen as precisions about how the controlling agent(s) act.

Simulated agents may appear closer to reality than a benevolent planner. However, understanding the way the simulated agents drive the transition in models is not easy, as they are generally much aggregated. Furthermore, their decision behaviors are usually calibrated on past and current actors' behaviors. Current models implementing simulated agents implicitly assume that the past and current contexts in which actors have behaved cannot change enough to generate changes in the types of actors and in their behaviors. This might lead to overestimating socio-cultural inertias.

On the contrary, the benevolent planner approach does not seek to reproduce past behaviors since the planner decides for the whole system's transition and dynamics. Hence this approach might underestimate socio-cultural inertias.

Note that studies using models with optimization methodology can describe their world either in terms of far-sighted, long-term financing agents (such as in (RTE, 2017)), or in terms of global system optimization (such as in (ADEME / Artelys, 2018)).

4. Model foresight informs about how far ahead transition agent(s) perfectly see

Some models assume an intertemporal foresight which means agents in the model (benevolent planner or simulated agents) make their decisions knowing in advance the whole trajectory up to the time horizon. Hence the whole trajectory is solved in one step (such as D-CAM model for a benevolent planner (CGDD, 2016) or TIMES for simulated agents (Energy Technology Systems Analysis Programme, 2016)).

Other models assume a myopic foresight, which means agents in the model make their decisions at each time step having some, but not all information about how the future will unfold, or having perfect and compete information but only for a given window of time.

For instance, PRIMES represents actors of the demand with a myopic foresight and actors of the supply with a perfect foresight. PRIMES usually "assumes a perfect foresight over a short time horizon for demand sectors and perfect foresight over long time horizon for supply sectors." (E3MLab, 2017)

Furthermore, having these information, simulated agents make investment decisions based on a preference for the present, that is they discount the future (modeled by a discount rate which is more or less disaggregated by sector, type of agent, etc). Similarly, the benevolent planner might optimize the transition with a given discount rate (such as in TIMES (Loulou, 2016)).

5. Top-down *versus* bottom-up categorization would be usefully replaced by a description of the modelled entities and their aggregation levels

Abundant literature divides energy modelling between two main categories: bottom-up and top-down models. Definitions differ according to modelers (Després et al., 2015), but some prominent points seem to be unchanging.

In top-down models, information is descending from aggregated to disaggregated levels (Després et al., 2015; Djemaa, 2009); they therefore provide an aggregated description of the system, which is represented in monetary units. Top-down models are also referred to as economic models. They originate from the Ramsey optimal growth model which inspired the DICE model and are based on a general equilibrium paradigm (Assoumou, 2006).

They rely on few aggregated variables – K: capital, L: labor, M: raw material, E: energy – which link the technical sphere to economic activity and technologies are implicitly represented *via* elasticities.

In bottom-up models, information is ascending: the description of the system is disaggregated and described with numerous technological variables. They are therefore referred to as technological models. Unlike top-down models, technologies, energy flows and technical characteristics are explicitly represented. Consumption and production of each technology are then summed from the bottom to the top.

Nevertheless, despite being one of the most common distinction between models, it seems to lose relevance over time with the emergence of hybrid models in which these descriptions are mixed together in such a way that some models tend to be "mostly bottom-up" or "mostly top-down" but cannot be purely classified as one or the other (IEA-RETD, 2013). Boulanger even questions this distinction as economic models are simultaneously "ascending" and "descending" regarding the interaction between volume (descending) and price (ascending). Moreover, he notes that macroeconomic models (as Corelli model) can adopt a highly disaggregated description as well as a bottom-up methodology (Boulanger & Bréchet, 2003).

This historical distinction is actually more fundamentally described in terms of which actors and objects are represented in the model and at which aggregation level. In other words, no need to say a model is bottom-up or top-down if one knows what technological objects and what deciding agents are represented in the model.

B. Modeled entities are the actors and objects in scenarios

The energy system and its surroundings feature not only complex interactions between elements at a large scale, but also complex behaviors of the elements themselves (Grandjean & Giraud, 2017). At the same time, modelers face technical limitations such as computing times, limited knowledge of the components of the system and of the way they behave, not to mention data deficiency and inaccuracy (Bhattacharyya & Timilsina, 2009). Simplifications of the system are thus needed, which is what defines the modelling approach.

Modelled entities must be selected taking into account those limitations. They belong to the sector scope and behave within the geographical scope and time horizon of the study.

These entities can represent physical assets (such as power plants, grid elements, storage equipment, consuming devices such as light bulbs etc), human beings or organizations (for example markets, finance decision-makers, households), or environment elements (for example CO_2 in the atmosphere) in the real world.

1. Resolutions and aggregation of modelled entities

It would be unfeasible to represent the energy system and all its surroundings electron by electron, cent by cent or $kgCO_2eq$ by $kgCO_2eq$, hence the need to aggregate some agents and define a level of resolution for each considered phenomenon. Some parts of the system are then described with more details than others, resulting in a specialization of models that the reader must be aware of since it can significantly affect the interpretation of results (such specializations appear in the bottom-up *vs* top-down distinction).

a. Aggregation level

Compared to the real world, entities can be represented in an aggregated way in the model. Here are examples of aggregation levels for different entities.

Power grid can be represented with different aggregation levels. For example, the European power grid may be represented as a set of interconnected copperplates, one per represented country. The copperplate is an aggregate of the power grid as if it were condensed in a single copperplate to which all the country's power plants and electric devices would be connected (Després et al., 2015). The power grid may be represented more finely with more regions and with more detailed equipment (different types of lines per level of voltage, equipment ensuring grid stability…).

The power generation has many representation possibilities too. Conventional productions can be described at the power plant level or aggregated by technology types. Several similar technology types can be aggregated (such as different technologies of wind turbines).

Economic agents are usually aggregated per sector (such as the iron and steel sector generating energy demand in PRIMES), or per technology (such as finance decisions for different power plant technologies).

The atmosphere is aggregated into a single figure when it comes to measuring GHG emissions.

R&D departments, industrialization departments or strategy departments of companies within a technology sector may be said to be aggregated when a "technology learning rate" is chosen. This rate usually represents the rate at which costs of a technology decreases with commercial experience. Even though most often no concrete explanation is provided about why the costs decrease, one might assume that they decrease because R&D and industrialization engineers lead to cost reduction, or because some parts of the activity are offshored to lower labor cost regions. In other words, making the explanation concrete reveals what actors are actually modeled, and how they behave.

b. Space resolution

Geographical resolution is the minimal space step between two modelled locations. Space resolution might be important for simulating renewables production (PV and wind), by precisely determining wind or sunlight levels for different locations.

It might also be important for representing highly deconcentrated power systems in which the specific place where electric device and equipment as well as production plants need to be precisely known to ensure a local power-supply balance (IEA-RETD, 2013).

c. Time resolution

Depending on the goal of the model, time step can vary from less than 1 s to several years. Typically, long-term transition models run on 1-year to 5-year time-steps whereas power system operation models typically run on sub-hour to 1-hour time-steps (see box hereunder).

A higher resolution enables to represent interactions with a higher dynamics between the represented entities. Several types of inertias can interact within a year in reality but could not be captured in a 5-year time-step model. For example, workforce structure evolution (such as the amount of available workforce in a given sector and the time it requires to modify this amount through training programs in a transition context), industrialization rates per technology, growth of material availability (such as rare earth magnets within wind turbines, or certain materials for photovoltaics) etc, need to be represented at a sufficient resolution to bring insight on the resulting inertia, especially within transformational scenarios (IEA-RETD, 2013).

Resolution adaptation for studying high shares of variable renewables in power systems

As explained in (IRENA, 2017) two different time steps are used in energy system models, to account for different processes happening at different time scales.

The first time step corresponds to the development of capital stock and investment decisions, happening on the long term. This is generally a 1 year to 5 year time step, which is precise enough to account for the long-lived capital stock evolution (whose lifetime ranges from 15 to 40 years or more) (see section on long term transition of the power system).

The second time step corresponds to the operation of the power system, taking into account the simulation of flexibility needs and how the proposed power supply system fulfils them, as well as other ancillary services (see section on power system operation) (IEA-RETD, 2013). Usually, modelers define time slices over which system operation is studied. They are chosen in order to represent the power demand and supply variabilities in order to study some aspects of flexibility. With few variable RES in the power system, these time slices account for demand variability[10]. With more RES, supply variability must be taken into account, which changes the time slices' definitions. Neglecting the variability of supply of variable RES could lead to a sub-optimal power mix, or to a power mix which is not operational. Hence scenario producers studying high power RES scenarios use hour time step models over whole years.

Similarly, geographical resolution has to be adapted for the study of RES supply, as supply largely depends on the precise location of the production plants. Typically, long-term models are not precise enough as they represent the power system through national nodes interlinked by interconnections. Hence in these models, RES generation would be the national average generation as if RES were evenly distributed over the whole territory. This can lead to sub-optimal power supply mixes. Furthermore, local grid structure cannot be modelled, hence the costs of its adaptation to more RES cannot be estimated finely, especially in case of deep restructuring. Finally, local phenomena such as voltage control cannot be modelled with such low resolutions.

Choosing the aggregation level and time/space resolutions depends on the needed precision, and the computation time. The more disaggregated entities are, the more entities must be individually modelled and the number of interactions between them might grow exponentially[11]. The higher space resolution, the more locations need to be modeled, and the higher time resolution, the more computational steps need to be performed to reach a given time horizon. Hence a tradeoff needs to be solved between these resolution aspects and precision needs. These choices also depend on data availability: if more entities are modelled, more data are required to calibrate them at first time step and to model their interactions between them. Similarly, to model PV and wind production at a high space resolution, weather data need to be available at the same, or a higher space resolution.

[10] For example, one week day and one week-end day for each season are represented, each of them being divided up in four 6-hour slices.
[11] n entities interacting together represent factorial n (n !) interactions.

2. Functions of entities are how they behave and interact

Represented entities interact with each other in the model. In that sense, each entity can be said to participate in different functions.

For example a coal power plant can have a CO_2 emission function, a power production function, power reserves and flexibility functions, a coal consumption function, a cost function, meaning that it is represented as emitting CO2, injecting power in the grid, participating in reserves and flexibility services for the power system, consuming coal and inducing costs respectively.

A market might have a price function as well as a supply and demand function, as it determines the clearing of the three variables. A financial decision-maker has an investment allocation among technologies function. Households may have a workforce function as well as a consuming different energy commodities, different goods and services functions and so on.

Among those functions, some might only be output functions (for example CO_2 might just be counted each year to produce an output, as opposed to being an input for a climate change feedback loop; cost might just be counted for total system expenses each year and so on) whereas others are interaction functions (injected power is consumed by other entities), and others are only input functions (for example the cost function of oil or gaz – their prices, or the power production of wind turbines depending on their location, etc).

Each function requires to characterize the entity which has this function through key characteristics of entities. For example, a coal power plant might have a coal consumption function, a power production function, and a power reserve function. Each of these functions need to be characterized: the plant consumes a given amount of coal per hour enabling it to produce a given amount of power per unit of consumed coal; the plant can increase its power by a given amount within a given amount of time to participate in reserves services etc. In the present framework, key characteristics of entities are dealt with in section about long-term transition of the power system.

Understanding the basics of a model requires to understand the main entities and main interactions between entities. As hundreds of different entities can be modelled, a simpler description can be provided by aggregating entities into meaningful groups sharing the same interactions with entities outside their groups. For example, all fossil fuel power plants may be grouped together in the simplified description of the model.

Key interactions between key entities can be represented within an interaction matrix, or with a graph. They can also be textually described.

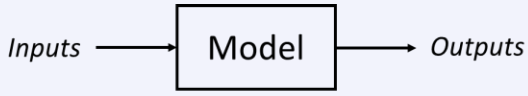
	Coal power plants	Transport	Households	Total expenses	Power	Fossil fuels	...
Coal power plants				X	X	X	
Transport			X	X	X	X	
Households					X	X	
Total expenses							
Power consumption							
Fossil fuels							
...							

Table 1: Interaction matrix between modelled entities for a fictive model.
Reading key: coal power plants participate in total expenses through their CAPEX and OPEX, they produce power, the consume fossil fuels; transportation is consumed by households; it participates in total expenses (in this fictive model) through vehicles production; it consumes power and fossil fuels, and so on.

Recommendations for scenario producers:

Future studies should be transparent about how the model(s) they used represent the real studied system. As described in the section about popularization, explaining a model requires transparency and a simplification of it. The modeled system as well as its similarities with the real system should be described, including the following aspects:

- The geographical perimeter as well as time horizon used in the model(s). A substantiation of compatibilities of the geographical perimeter as well as time horizon used in the model(s) **with scenarios' needs** (including the driving questions) should be performed.
- The sector scope of the model(s). A substantiation of the compatibility of the sector scope of the model(s) **with scenarios' sector scope and published results** should be performed. *E.g., if scenarios talk about lifestyles, or purchasing power, does the model enable to compute lifestyle changes, or purchasing power of households? Otherwise, how are these questions handled by the study?*
- Geographical resolution of the model(s). A substantiation of the compatibility between geographical resolution of the model(s) and the main published results should be provided, in line with the driving questions. *For example, if the lowest level of resolution is the country level, no results can be provided on a country's regions level. Typically, if PV resources are evaluated based on a country average, their repartition across the different regions within the country cannot be provided from model's results.*
- Time step of the model(s). A substantiation of the compatibility between time step of the model(s) and the main published results and their interpretations should be provided, in line with the driving questions. *E.g., infra year dynamics cannot be described by a one-year time step model. For power system (see section about power system operation), infra hour to hour time-steps may be required to provide results on the power system stability, depending on the structure of the proposed system and its share of variable renewable energy sources.*
- The inputs and outputs of the model. A very simple diagram should be provided to show the inputs and outputs of the model (Cao et al., 2016).



- The main entities which are represented in the models. These entities are objects and agents existing in the real studied system. *E.g., technology learning rate cannot be seen in the real world; however, they may represent the decisions from the aggregation of R&D and industrialization departments of a sector's companies in the real studied system.*
- The level of aggregation for each entity, and its consistency with the main published results and their interpretations, in line with the driving questions. *E.g, all nuclear power plants may be aggregated in a single object in the model. This would not be compatible with describing in the scenario a precise nuclear phase-out schedule.*
- The main interactions of the described entities. These interactions can be described using interaction matrices, or graphs, and/or through text, or any other mean suiting the scenario producer. This representation should clearly show what entities are inputs and what entities are outputs. *E.g., R&D and industrialization departments of the wind turbines sectors may interact with wind turbines through time to decrease their costs and improve their load factors by 2% every time 1000 wind turbines are installed. These entities, through their technology learning rate, can be an input.*

Bibliography

ADEME. (2014). *Visions énergie climat 2030/2050 - Quels modes de vie pour demain ?* (Nº 8102; p. 132).

ADEME / Artelys. (2018). *Trajectoires d'évolution du mix électrique 2020-2060 - Synthèse*.

ARTELYS / European Commission. (2017). *METIS Technical Note T6 - METIS Power SYstem Module* (p. 43).

Assoumou, E. (2006). *Modélisation MARKAL pour la planification énergétique long terme dans le contrexte français*.

Bhattacharyya, S. C., & Timilsina, G. R. (2009). *Energy Demand Models for Policy Formulation - A comparative Study of Energy Demand Models* (Nº 4866). The World Bank.

Bhattacharyya, S. C., & Timilsina, G. R. (2010). A review of energy system models. *International Journal of Energy Sector Management*, *4*(4), 494‑518. https://doi.org/10.1108/17506221011092742

Boulanger, P.-M., & Bréchet, T. (2003). *Une analyse comparative des classes de modèles*.

Callonec, G., Landa Rivera, G., Malliet, P., Saussay, A., & Reynès, F. (2016). Les propriétés dynamiques et de long terme du modèle ThreeME. Un cahier de variantes. *Revue de l'OFCE*, *5*(149), 47‑99.

Cao, K.-K., Cebulla, F., Gómez Vilchez, J. J., Mousavi, B., & Prehofer, S. (2016). Raising awareness in model-based energy scenario studies—a transparency checklist. *Energy, Sustainability and Society*, *6*(1). https://doi.org/10.1186/s13705-016-0090-z

CGDD. (2016). *Trajectoires de transition bas carbone en France au moindre coût*.

Connolly, D., Lund, H., Mathiesen, B. V., & Leahy, M. (2010). A review of computer tools for analysing the integration of renewable energy into various energy systems. *Applied Energy*, *87*(4), 1059‑1082. https://doi.org/10.1016/j.apenergy.2009.09.026

Després, J., Hadjsaid, N., Criqui, P., & Noirot, I. (2015). Modelling the impacts of variable renewable sources on the power sector: Reconsidering the typology of energy modelling tools. *Energy*, *80*, 486‑495. https://doi.org/10.1016/j.energy.2014.12.005

Djemaa, A. (2009). *Modélisation bottom-up, un outil d'aide à la décision long terme pour les mesures politiques en matière d'énergie et d'environnement: le modèle TIMES appliqué aux industries grandes consommatrices d'énergie*. 417.

E3MLab. (2017). *PRIMES Model, Version 6, 2016-2017 - Detailed model description*.

E3Modelling. (2018). *PRIMES MODEL VERSION 2018 - Detailed model description* (p. 221).

Energy Technology Systems Analysis Programme. (2016). *Documentation for the TIMES Model*.

European Commission. (2011). *Energy Roadmap 2050 - Impact assessment and scenario analysis*.

Grandjean, A., & Giraud, G. (2017). *Comparaison des modèles météorologiques, climatiques et économiques : quelles capacités, quelles limites, quels usages ?*

Herbst, A., Toro, F., Reitze, F., & Jochem, E. (2012). Introduction to Energy Systems Modelling. *Swiss Journal of Economics and Statistics*, *148*(2), 111-135. https://doi.org/10.1007/BF03399363

IEA-RETD. (2013). *Re-assume - A Decision Maker's Guide to Evaluating Energy Scenarios, Modeling and Assumptions*.

International Energy Agency. (2018). *World Energy Model Documentation - 2018 Version* (p. 82).

IRENA. (2017). *Planning for the Renewable Future - Long-term Modelling and Tools to Expand Variable Renewable Power in Emerging Economies*.

Keramidas, K., Kitous, A., Schmitz, A., European Commission, & Joint Research Centre. (2017). *POLES-JRC model documentation.*

Loulou, Ri. (2016). *Documentation for the TIMES Model - PART I* (p. 151). Energy Technology Systems Analysis Programme.

RTE. (2017). *Bilan prévisionnel de l'équilibre offre-demande d'électricité en France*.

van Beeck, N. (1999). *Classification of Energy Models*. 25.

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The Shift Project

The Shift Project, a non-profit organization, is a French think-tank dedicated to informing and influencing the debate on energy transition in Europe. The Shift Project is supported by European companies that want to make the energy transition their strategic priority & by French public funding.

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Boundary conditions for energy transition scenarios

Technical file #3 – Draft version

Information and recommendations for scenario producers

This document is part of a set of 12 technical files. These files have been produced by *The Shift Project* after one year and a half of research and experts consultations on the different aspects of energy transition and the future studies around these aspects.

Our project, "Power Systems 2050 – Guidelines for design," started in January 2018, with the participation of 10 experts who defined the key subjects which according to them have to be collectively tackled by future studies about the power transition. *The Shift Project* then investigated each of these subjects, consulting in total 40 experts, organizing 4 workshops, and reviewing a large bibliography, including a dozen of future studies about power (and energy) transition at different geographical scales.

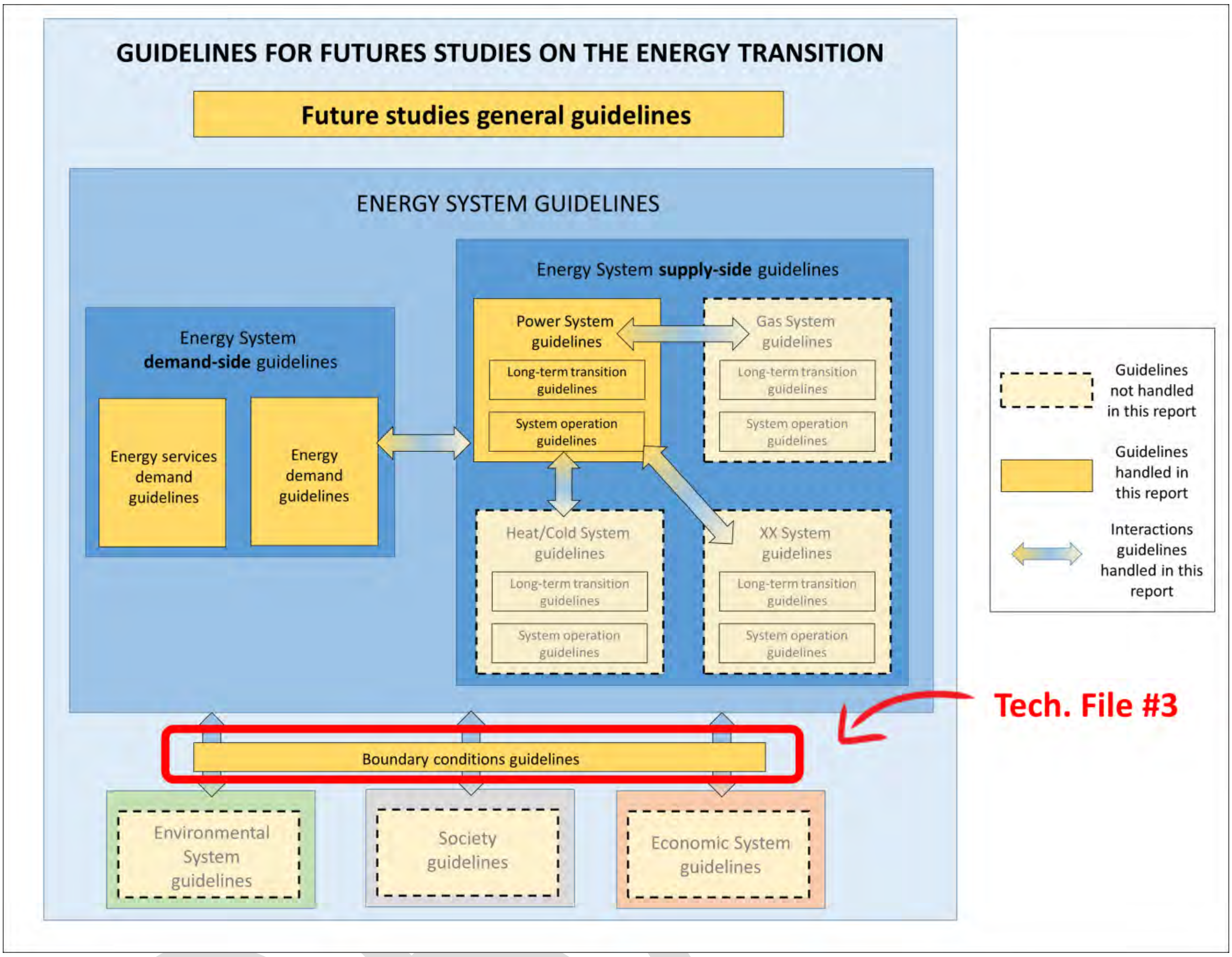
The goal of this project is to produce a set of guidelines addressed to scenario producers. These guidelines seek to foster transparency and consistency *within* future studies and to develop a common language *across* studies. By defining a number of important items which are key to deal with in future studies, we actually propose a study template which enables a better understanding of the location of each proposed scenario on the tree of possible transitions. Once again, the objective is not to *rank* studies, or scenarios, but rather to *compare* them to get a better collective overview of the different aspects of the transition (what are the differences between studies in terms of driving questions, hypotheses, models, methodology, results?).

Several aspects of the energy transition are handled in these technical files. However, on the energy supply-side only the power system has been studied. The main reason for this choice is that we had to start from somewhere with limited resources, and the power system seemed to be a key system to study in the energy transition context, towards a low-carbon economy, as shown by the growing number of future studies focusing on this system. However, the guidelines we propose could be completed by analyzes on the other energy supply-side systems (the gas system, oil system, heat system and so on).

Each technical file tackles several aspects of future studies for the power (and energy) transition. Here is the complete list of the technical files produced during the project:

#	Technical file title
1	Future studies on the energy transition
2	Energy transition models
3	Boundary conditions for energy transition scenarios
4	Long-term evolution of energy consumption in energy transition scenarios
5	Lifestyles and consumption behaviors in energy transition scenarios
6	Long-term evolution of the power system supply-side in energy transition scenarios
7	Power system operation in energy transition scenarios
8	Impact assessment in energy transition scenarios
9	Transition desirability in energy transition scenarios
10	Environmental assessment of energy transition scenarios
11	Economic evaluation of energy transition scenarios
12	Employment assessment of energy transition scenarios

Altogether, these files cover the fields described on the following map of the guidelines for future studies on the energy transition. The document you are reading covers the red-circled topics.



In addition to these technical files, three complementary notes have been produced as specific focuses on the following aspects: material criticality in energy transitions (in French, to be translated and added to technical file #10), levelized cost of electricity (LCOE) in energy transition future studies (in French) and discount rate in energy transition future studies (in French).

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Reading keys

Explanation box, containing key information for a better overall understanding of the subjects.

Recommendations to scenario producers:

These boxes contain the recommendations for scenario producers.

The word “should” means that scenario producers, if they are to follow the guidelines, must substantiate the corresponding point. The words “may” or “might” relates to suggestions, ideas to help the scenario producer respond to the point.

Questions in italic are examples of questions scenario producers might ask to substantiate the points. They are here in an illustration purpose.

Phrases in italic relate to words which are being defined and will be subsequently used in the framework.

Phrases which are highlighted in yellow refer to other technical documents of this series.

I. Boundary conditions: what modeled actors cannot, or are not willing to modify

A. Boundary conditions depend on the perimeter of the considered system and on the chosen model

The notion of boundary condition is linked to what the energy system actors which are modelled cannot, or are not willing to, modify (Samadi et al., 2017). For example:

- Oil prices for Europe cannot be modified by modelled actors.
- European actors are not willing to act on demography.
- Political objectives or measures are seen as boundary conditions. Indeed, the studies within our scope are addressed to policy-makers, hence policy-makers are not included in the modelled system. Instead, their possible decisions (when considered in studies) are exogenous hypotheses which are imposed on the modelled system.

Boundary conditions are usually part of the storyline before being derived as exogenous hypotheses.

More technically, boundary conditions are the conditions which are imposed on the considered system (either the entire energy system (ES) or the power system (PS)) and which partly drive its behavior.

Of course, systems outside the perimeter and interacting with the modelled system (such as other energy sub-systems if the studied system is power system) are parts of boundary conditions.

1. The energy system can be broken down by energy carrier and by supply or demand-side

The energy system is composed of several subsystems, which can be separated by the *carrier* they produce, transport and consume (electricity, gas, hydrogen, oil, heat, etc). Each of these subsystems is composed of a *supply-side system* and a *demand-side system*. These different subsystems interact with each other, directly (supply-side interactions) or indirectly (demand-side interactions). On Figure 1, each carrier is represented with a different color and a few supply-side interactions are represented.

The supply-side system ranges from the production or import point down to the point before end-consumption of the carrier, or before transformation; it includes self-production (e.g. from roof solar panels) and storage systems (e.g. pumped hydro storage, or batteries).

The demand-side system is composed of the set of equipment, appliances or industrial processes consuming the carrier[1]. For example, washing machines, cars, trucks, industrial processes, heating systems and so on are included in the demand-side system.

[1] Physically speaking, consumption corresponds to the transformation of the energy carrier into useful energy (such as movement, light…) and heat.

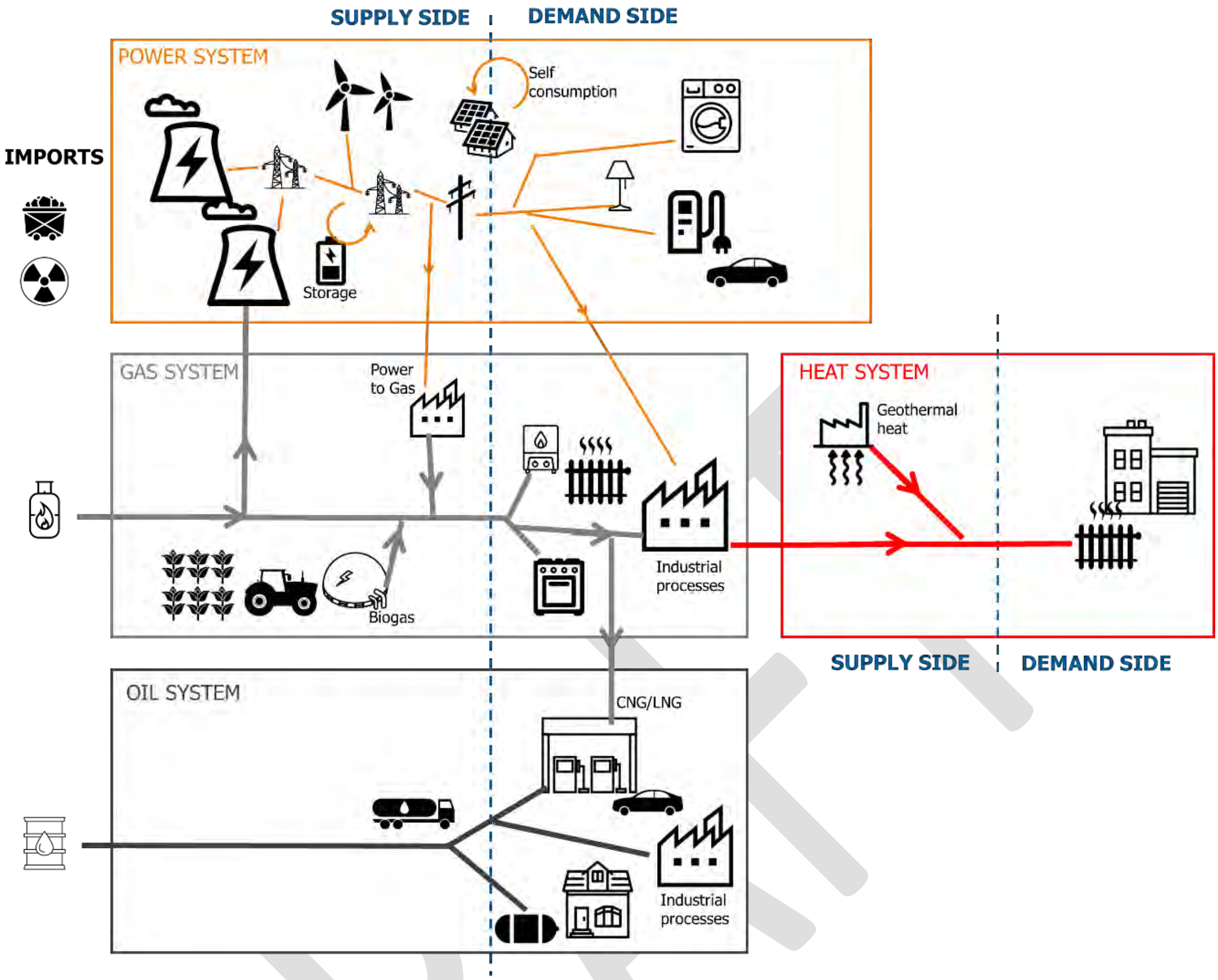

Figure 1: Simplified description of the energy system to illustrate what we call energy subsystems (the power system, the oil system and so on) and the distinction between supply-side and demand-side for each energy subsystem. Not all the energy subsystems are represented (hydrogen, coal, nuclear and so on could be represented), and no hierarchy between the subsystems is assumed here. Some interactions between the subsystems are represented, but not all of them.

2. Boundary conditions **of the studied system depend on… the studied system**

As shown in Figure 2, scenarios assume the energy system (ES) evolution is driven by several types of boundary conditions. In future studies, the most usual boundary conditions are the following:

- lifestyles and behaviors, which impact energy demand and may impact the whole energy system development through desirability issues (see desirability section);
- technologies and their evolutions impact both demand (more efficient fridges or cars…) and supply (larger wind turbines, more flexible nuclear plants, operational large-scale Carbon Capture and Storage…);
- demography impacts demand level, as well as lifestyle trends through age structure;
- macroeconomic situation, such as GDP, provides information about the overall size of the economy in which the transition happens;
- industrial offshoring pattern or, conversely, industrial activity increase impacts demand level;
- policy framework(s), through taxation and public investments, regulations, standards and social objectives may impact the whole energy system in different fashions;
- prices of imported goods and materials may impact both demand-side and supply-side systems because it impacts both demand-side and supply-sides technologies prices. Similarly, prices of imported fuels (mainly coal, gas, oil, uranium) impact both the demand-side (impacts on the prices of internal

combustion engine (ICE) car use, of gas heating…) and supply-side (especially for the PS) through variations in the prices of fuels feeding power plants;

- availability of local resources such as renewable energies impact the supply-side capability to fulfill energy demand with renewables.

When studies focus on the PS, they add direct boundary conditions to the PS: those posed by the interactions with other energy subsystems.

Such interactions can happen on the supply-side, corresponding to energy transformations from one carrier to another one. They can also happen on the demand-side, corresponding to carrier shift through technology shift when several technologies associated with different carriers compete for providing the same energy service (such as mobility, which can be performed through electricity carrier, oil carrier, gas carrier, or hydrogen carrier).

The evolution within those different energy carriers are also driven by the ES boundary conditions. Hence, in a way, ES boundary conditions affect the PS both directly (for example, lifestyles changes can directly impact the PS evolution) and indirectly (for example, very cheap gas imports may lead to increase gas use in heating at the expense of electricity).

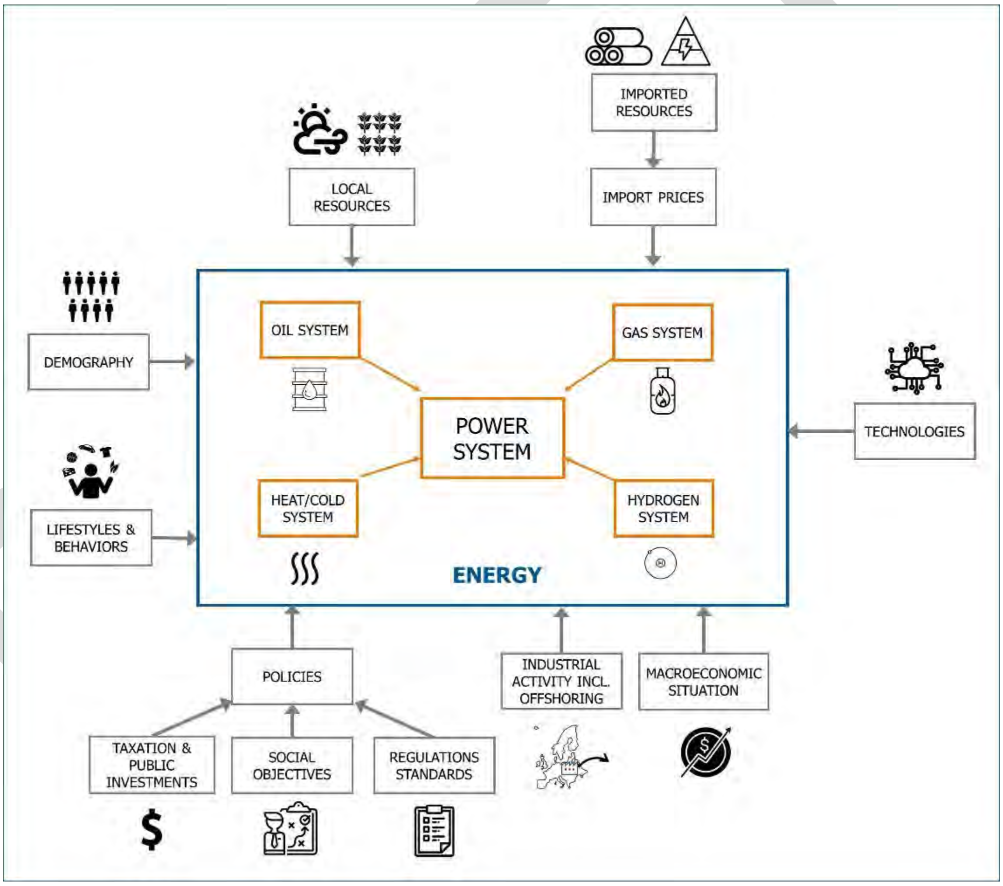

Figure 2: The usual boundary conditions for the energy system and the power system in future studies.

3. Boundary conditions are driven by the model used

As previously described, conceptually speaking boundary conditions are what simulated agents cannot, or are not willing to modify. Simulated agents are actors driving the energy mix and simulated in the model[2]. Hence the notion of boundary condition is tightly linked to that of models. Boundary conditions are translated in models into what we called "exogenous variables and parameters" (see future studies). Within a scenario, each exogenous variable and parameter is set to a given trajectory which is imposed to the simulated agents by the modeler. However, across scenarios within a future study, those variable parameters can take different trajectories so as to show the

[2] Note that even optimization models can be considered as simulating a benevolent planner which would be able to drive the energy system by its only will.

effects of setting them differently. A boundary condition is a hypothesis that the model requires in order to run properly.

As studies do not use the same models, the nature of these variables differs across studies.

Typically, benevolent planner models of the power supply-side (such as the one used by (ADEME, 2015; ADEME / Artelys, 2018; ECF, 2010; Lappeenranta University of Technology / Energy Watch Group, 2017)) require boundary conditions on the following aspects of the transition: power demand evolution (consumption due to lifestyles and behaviors, as well as consumption from industrial processes within the geographical perimeter, both depending on demographics), available technologies, evolution of their technical characteristics and prices, fuel prices, available local resources, interconnections with neighbor regions, and social objectives the benevolent planner wants to achieve (such as reducing CO_2 emissions down to a given level, or minimizing the cost of the supply-side transition).

Benevolent planner models for the whole energy system (such as (ADEME, 2012; Association négaWatt, 2014; Association négaWatt, 2017; Fraunhofer ISE, 2015)) require the same type of hypotheses but applied to the whole energy system.

Simulated agents models (such as (DGEC/CGDD/ADEME, 2015; OECD/IEA, 2017; RTE, 2017) and all studies using PRIMES model, such as (European Commission, 2011; European Commission, 2016; SFEN, 2018)) require hypotheses about the political frame and political objectives, about the available technologies, the evolution of their technical characteristics and prices, the prices of fuels, and macroeconomic situation, such as GDP evolution (which actually translates largely unspoken hypotheses about global constraints on the economic system).

Note that lifestyles and behaviors evolutions are not a boundary condition for simulated agents' models because they model them by assuming they are ultimately determined by the political frame and objectives. In other words, they have *endogenized* lifestyles and behaviors by modeling them, generally through elasticities to price (see Figure 3).

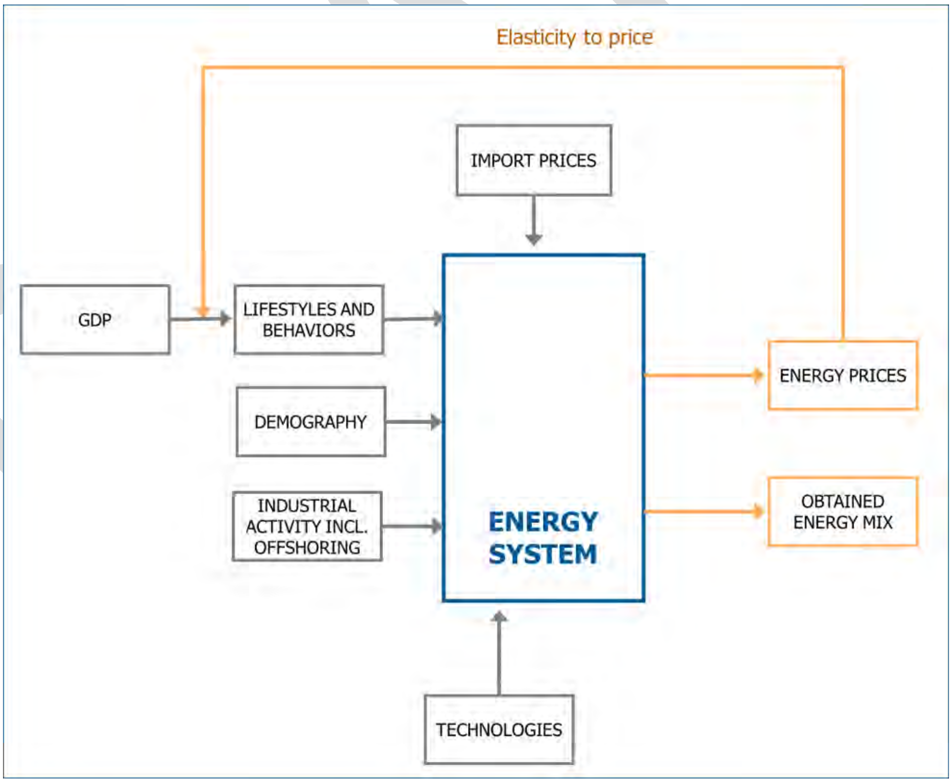

Figure 3: Illustration of the endogenization of lifestyles and behaviors.

Similarly, some models require as input the characteristics of each technology year after year whereas some others endogenize a part of the evolution by assuming a learning effect (see Figure 4). In this case, the boundary condition is one of learning effect parametrization (the technical and cost improvements with every doubling of the production, for instance).

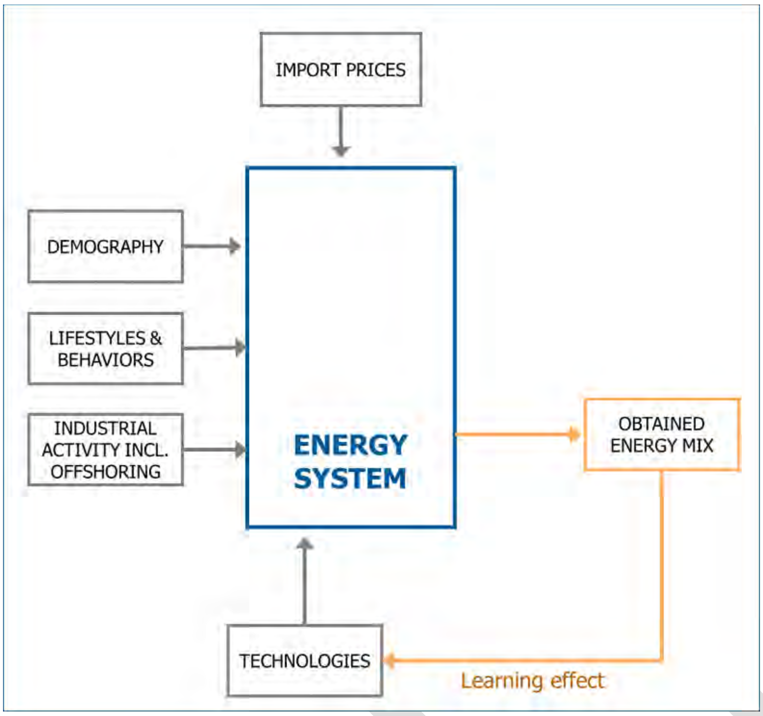

Figure 4: Illustration of the endogenization of the learning effect of technologies.

A very few models endogenized the effects of some planetary boundaries, or of the financial sector. (Bovari, Giraud, & Mc Isaac, 2018) modeled the climate change feedback on the economy through different damage functions (see Figure 5) and modeled the financial sector through a stock-flow consistent monetary macrodynamics. (Donella H. Meadows, Randers, & Meadows, 2004) modeled the feedback loops between different planetary boundaries and the economy.

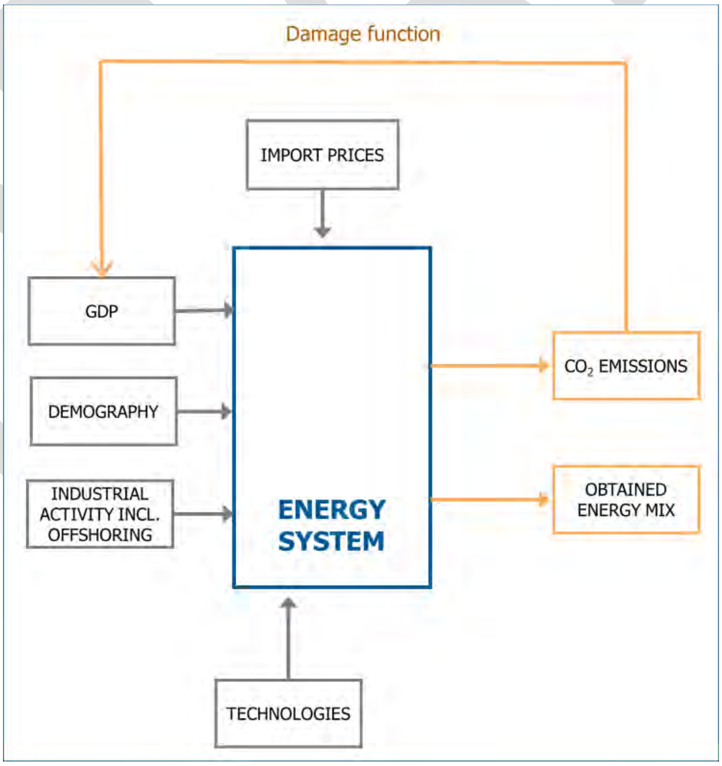

Figure 5: Illustration of the endogenization of the effect of climate change on the economy, through a damage function.

Recommendations to scenario producers

A list of the main boundary conditions fixed for the different scenarios should be provided.

B. In current scenarios, planetary physical limits are poorly, or not at all, taken into account

In current future studies, planetary boundaries[3] and non-renewable resource availability (which we call together the *physical limits*) are not taken into account through boundary conditions.

This might not be a problem for scenarios in which the proposed energy transition prevents from coming too close to these physical limits, though. Often, transformational scenarios have a social objective, or policies leading to a dramatic decrease of greenhouse gases (GHG) emissions over the scenario timeframe. Hence, in these scenarios climate change may not have significant physical impacts on the economy since mitigation effort has been great enough. (that is, the climate change boundary is not transgressed in these scenarios[4]). Presumably, in scenarios which do not transgress the climate change boundary, a GHG emissions assessment only is enough to show the absence of transgression.

This might not be a problem neither if the physical limits are endogenized in the model used by the study so that they do not have to be taken into account through boundary conditions. However, as just shown, only a very few models have this capability.

Hence, most scenarios (and even transformational scenarios):

- Do not take into account the impacts of the already triggered climate change, which may be significant and which will increase (even modestly) during the scenario timeframe. Indeed, no scenario implements a feedback loop between climate change and its impacts on the economy, demographics, or any human activity in general. This could be done through different boundary conditions, such as hypotheses on demographics (e.g. including migration waves), hypotheses on adapted consumption behaviors and supply-side adaptations with climate change (as mentioned in sections about energy consumption and transition of the power supply-side), or directly through a macroeconomic hypothesis about GDP. This is not performed yet to our knowledge.
- Do not assess the impacts on other planetary boundaries or on non-renewable resources. Indeed, in a similar fashion as for climate change, no feedback loop is implemented in current models used by future studies, and those physical limits are neither described in storylines nor integrated in boundary conditions. They could be integrated in boundary conditions through higher, and more volatile, import prices for non-renewable resource, through impacts on demographics, GDP and so on.

For scenarios which do not have the objective of reducing GHG emissions (this is typically the case for reference scenarios), physical limits may be transgressed. As no feedback loop is implemented in models, those scenarios are openly unrealistic (not to mention, extremely risky), sometimes without being clear about it.

Recommendations to scenario producers

Scenario producers should make their strategy about planetary boundaries and non-renewable resources (physical limits) explicit. They should first be explicit for each scenario if they consider those physical limits or not. If they do:

- They should detail if those limits are endogenized in the model they used and if yes how.
- If those limits are not endogenized, scenario producers should detail if they are embedded into the boundary conditions and if yes how

[3] "The boundaries define a safe operating space for humanity that should not be transgressed if we want to maintain stable conditions at the Earth System level." (The University of Cambridge Institute for Sustainability Leadership / Kering, 2017)

[4] Following the planetary boundary framework vocabulary.

- If the limits are neither endogenized nor embedded into boundary conditions, scenario producers should explain how those limits are integrated into the scenario design, or provide a narrative to substantiate the fact that they are not significantly impacting for the scenario.

If those limits are not considered, this should be clearly mentioned. A qualitative analysis should be provided to detail the potential impacts on the scenario of taking those limits into account, or to substantiate the absence of impact of taking them into account.

C. Boundary conditions for the energy system

1. Lifestyles and behaviors assumptions greatly drive energy, and power, demand

Lifestyles and behaviors (including investment behaviors in equipment) greatly drive energy demand through energy services demand (lighting, cooling, washing), demand for goods (requiring energy to produce them through industrial processes), and energy intensity (investments in more energy efficient appliances, in house insulation, or through practices changes such as telework or carpooling) (see section on lifestyles).

Lifestyles and behaviors largely depend on policies, economic conditions and available technologies, which are also part of boundary conditions.

Lifestyles in interaction with the energy system also determine energy consumption on the near-term, through daily behaviors. Hence some aspects of daily habits may have an importance on instant demand, especially for the power system as electricity cannot be stored per se (unlike gas, oil, coal or uranium) (see power system operation).

Recommendations to scenario producers

Scenarios should make explicit the behavior changes happening in their scenarios (either in the storyline or in the results) and explain them for example through the links between those changes and other boundary conditions (such as policies, economic conditions). Also see lifestyle section.

2. Assumptions about technologies play a key role in scenarios

In general, scenarios do not model the emergence of new technologies which can be used in the modeled system. Instead, scenarios include in their storylines a list of technologies which are used in the power system, and the date at which they are mature. They also sometimes describe the way technologies evolve during the scenario timeframe, especially in terms of costs reductions (technology learning rate). Very rarely do they explain why such reductions would happen. Instead, those hypotheses derive from historical projections or expert judgement.

The availability of technologies in scenarios as well as the date they become mature are key drivers of the energy system supply-side evolution. For example, the availability of a mature and efficient power-to-gas technology provides season flexibility for power systems with a large share of VRES, enabling the integration of significantly more VRES. The availability of mature and efficient CCS technologies in scenarios with strong carbon constraints dramatically changes the power supply-side mix: coal can remain a major power producer if CCS is commercially mature, but must be replaced otherwise.

Demand-side technologies (cars, lightbulbs, industrial processes…) are also assumed to improve, for example by reaching best available technologies (Association négaWatt, 2014; European Commission, 2011).

The evolutions of technology prices (demand-side equipment or supply-side technologies) are also key drivers of the energy system evolution in scenarios, especially for studies using models which determine the energy system through decisions based on prices, such as simulated agents models or benevolent planner models seeking costs minimization (see section on supply-side LTT).

The availability of some technologies can play a great role for the near-term control of the PS. This is the case for all the technologies providing anciliary services, as described in the operation section.

see section on supply for more details about technologies

Recommendations to scenario producers

Scenario reports should provide the list of technologies used in the scenario, their date of maturity, the nature and speed of their improvements (in terms of costs or technical characteristics) and provide explanations for these elements. Why do technologies improve? What cost component decreases in total cost and for what reason?

3. In scenarios, demography is an uncontrollable certainty

Demography is a key driver of ESs, as it is a key driver for demand. In future studies, demography is a boundary condition for the energy system. Indeed, in models there is no feedback from the ES to demography so demography is imposed to it. Demography is determined through the storyline, and data are usually selected from demographic projections. Scenarios do not perform any sensitivity analyses on demography, which shows this variable is considered as suffering no uncertainty.

Recommendations to scenario producers

Scenario reports should make their demographic assumptions explicit, as well as the source of data they used.

For each scenario within a study, scenario producers should substantiate the fact that demography is not affected by the proposed energy transition.

4. A great diversity of policy tools affecting individual and corporate behaviors

Political framework (taxation system and regulations/ standards) affect individual behaviors as well as companies behaviors.

a. Tax system and public investments

Tax system is implemented by the State and as such it is considered as a boundary condition for the ES in scenarios. A tax system plays a role on households and companies behaviors. In order to be an efficient incentive on the long-run, a tax system must ensure stability for targeted actors.

Here are different examples of tax/subsidies having effects on the long-term evolution of the ES:

- feed-in tariffs for production ensure a stable price for several years; hence it plays a role in the long-term bankability of production plants benefiting from it, fostering the investments in these plants.
- A carbon tax with a clear, defined in advance, value provides key incentive for investors to favor the phasing-out of high carbon production and consumption and the emergence of low carbon production and consumption.
- Subsidies for building insulation for households foster the greater average energy efficiency of residential buildings.

The choices of taxation in scenarios can lead to very different pathways. For example, the specific evolution of a carbon tax determines if a scenario mainly implements gas power plants or coal power plants. As mentioned in the desirability section, taxation system may lead to, or solve, desirability issues. Scenarios often neglect this aspect.

Taxes partly drive the behaviors and choices of economic agents in scenarios because it impacts the costs and benefits associated with these behaviors and choices. Considerations on whether or not taxes should be included in total cost assessment of the transition can be found in section about economic evaluation.

Some taxes may have effects on the near-term behavior of the PS: a carbon tax leads to favor production by low carbon means, which may have impacts on the flexibility and inertia of the PS, as explained in the operation section.

Public investments are also a lever to foster the energy transition when public infrastructure need to evolve. For example, (Association négaWatt, 2014) proposes investment in public transportation; (ADEME, 2014) proposes to develop a finely meshed bike network in urban areas, which requires public investments.

b. Regulations and standards

Regulations and standards can lead to:

- Improved energy efficiency and reduced emissions of technologies on the demand-side and on the supply-side through more stringent production standards. Examples include standards on car emissions, standards on the energy efficiency of industrial processes, on coal power plants emissions or on fridges energy efficiency.
- Improved energy efficiency through regulations favoring information about it (labelling regulations for appliances and buildings).
- Energy demand reductions through regulations favoring practices and new organizations, such as car bans in city-center, new regulations on territory planning, new regulations on building insulation and heating system, etc.

Studies produced by the European Commission put into play a large set of European directives including regulations and standards (European Commission, 2011; European Commission, 2016).

c. In simulated agents scenarios, any social objective can be reached through policies (in particular, any GHG emission cap can be respected through a carbon price)

In scenarios, social objectives are boundary conditions for the ES as it is imposed by the benevolent planner (in the benevolent planner model philosophy), or policy makers (in the simulated agents model philosophy). Social objectives are very often about GHG emissions and security of electricity supply, more rarely about air pollution and access to energy. They are key drivers of the LT evolution of ES as they are considered in models as hard constraints (usually they are backcasted components, see section on future studies).

Studies using a benevolent planner philosophy perform some form of optimization or systematic method to reach an optimal point assuming these social objectives are reached (ADEME, 2014; Association négaWatt, 2014; Fraunhofer ISE, 2015; Barton et al., 2018).

On the opposite, studies using a simulated agents philosophy implement policy levers such as taxes, standards, regulations etc in their transformational scenarios in order to reach these social objectives (ECF, 2010; European Commission, 2011; SFEN, 2018; IIASA, 2012). In other words, in these studies, dedicated policy levers lead to reaching the social objectives: a functional equivalence exists in those scenarios between social objectives and policy levers. More concretely, social objectives are set before the model is run, and then the policy boundary conditions are tuned in order to reach the social objectives.

The most typical example of this practice is the use of the carbon pricing policy lever to reach a GHG emission target: in many simulated agents transformational scenarios, carbon price is computed in such a way that simulated agents behave to reach the GHG reduction objective, such as in (European Commission, 2011; IIASA, 2012).However, in some studies, when the carbon price which is required to reach the GHG emissions objective is above an arbitrarily high value, the scenario is considered as “infeasible”, such as in (IIASA, 2012).

(ECF, 2010) uses carbon price to define the carbon abatement measures which are implemented in the scenario: all the measures whose abatement cost is lower than 100\$/tCO_2 are assumed to be implemented.

For their Sustainable Development Scenario, World Energy Outlooks (WEOs) define a carbon price trajectory (reaching 140\$2016/tCO_2 by 2040 for WEO 2017 and 140\$2017/tCO_2 for WEO 2018) to reach emissions targets (International Energy Agency, 2017; International Energy Agency, 2018; OECD/IEA, 2017; OECD/IEA, 2018).

In some scenarios using PRIMES model, assumed carbon tax or cap and trade mechanisms alone are not sufficient to reach the CO_2 emissions reduction. In those scenarios, PRIMES model computes an implicit carbon value corresponding to the achievement of the CO_2 emissions objective and make all the economic agents act as if their consumptions included this carbon value in their prices. In other words, economic agents act as if they perfectly had in mind the CO_2 emissions objectives to optimize their decisions (E3MLab, 2017).

All these mechanisms use carbon price, or carbon implicit value, to model the changes in economic behaviors so as to respect a set GHG emissions objective. As a consequence, the carbon value which is reached actually reflects the intensity of economic behavior changes. These methodologies to curve behaviors may hide desirability issues because they use a single value to depict behavior changes, which is not concrete enough about how behaviors actually change during the scenario. Desirability issues should be concretely discussed in these studies (see section on desirability).

Recommendations to scenario producers

A scenario strategy about taxation and public investment, regulations and standards, and social objectives should be defined and justified. It should include considerations on the decision to study this subject or not. This choice depends on the Planning Question and on the study overall strategy. In case the subject is studied, the different aspects of it which are considered should be reported, and their links to the study strategy should be outlined.

- Type of policy tool which is used
- Main effects of this tool

Policy tools as well as social objectives and in particular carbon value lead to economic behavior changes (either through end-consumption behaviors or through investment decisions for household; through investment decisions for industries and corporations). Scenarios should provide details about possible behavioral trend discontinuities for individuals' behaviors and explanations about why those discontinuities are accepted in the scenario (see lifestyles section).

5. Prices of imported materials and goods are not a subject for energy transition scenarios

Prices of imported materials and goods are usually not part of the boundary conditions of the ES in scenarios. However, they might have an importance for ESs requiring more physical capital to produce energy (such as ESs with high RES shares).

Depending on the behaviors of other regions of the world in their materials consumption, supply of some materials might not be able to follow demand, which would impact prices. This would lead to price variations for the technologies requiring such materials.

Hence technologies prices depend on the world context about material resources, both for demand side technologies (such as telecommunication devices, or electric vehicles) and for supply side technologies.

However, we could not find any scenario which consider such prices evolutions even though they estimate costs; they all determine prices evolutions of the technologies independently of materials, or fuel prices. Hence no inflation effect is accounted for in scenarios from rises in commodity prices (ANCRE, 2013; ECF, 2010; European Commission, 2011; European Commission, 2016; Greenpeace, 2015; Lappeenranta University of Technology / Energy Watch Group, 2017).

The underlying assumption of making technology prices independent from import prices for goods and materials is that no significant evolution of these prices happens, in particular no shortage of materials and no geopolitical tension with exporting regions will happen during the scenario timeframe. Details on material resources criticality can be found in the dedicated analysis note.

For world scenarios, considering local prices may be interesting if disparities in world markets exist. However, the ultimate boundary condition for world scenarios is the availability of yearly flows of materials and fuels and how fluently they are distributed to balance demand (viscosity could happen with geopolitical tensions).

Recommendations for scenario producers

Scenario producers should report about whether or not the prices of the technologies involved in their scenarios are linked to material resources availability, and substantiate their choice.

In case they do, scenarios should provide elements to explain the evolution of key material resources prices in their storylines.

6. A very low diversity of assumptions about GDP evolution

For some scenarios, GDP is an essential input which determines the aggregated demand level and hence is a key driver of consumption behaviors, determining in turn both demand and supply sides of the energy system.

Scenarios use different strategies to determine their GDP evolution hypotheses: either they base them on a reference source which is judged robust enough to be accepted by the rest of the scenario community, or they use a storyline to substantiate the assumed evolution.

For example, the European Commission reference scenario (European Commission, 2016) uses a storyline explaining why GDP growth would be sustained at a 1.5% rate on the long run:

"*Over the longer term the impacts of the financial crisis are projected to fade away, structural reforms start to yield results, labour markets improve and more supportive policies and financing conditions are projected to be put in place sustaining the growth in the EU Member States.*"

This scenario is then used as a base scenario for the EUCO scenarios (E3MLab & IIASA, 2016), which are themselves a basis for scenarios of the SFEN study (SFEN, 2018). It can be deduced – even though it is not explicitly said – that GDP assumptions for all the scenarios of those studies are derived from this narrative.

Usually, these hypotheses are used to build a baseline scenario. Then a storyline or a quantitative assessment is used to justify the fact that GDP evolution is the same in the transformational scenarios as in the baseline scenario.

For example, the transformational scenarios of the European Commission' roadmap have the same GDP evolution as the Reference scenario following this line of reasoning:

"[…]*in the context of necessary reductions by developed countries as a group it is assumed that competitiveness effects throughout decarbonisation would be rather limited. Therefore, the decarbonisation scenarios are based on the same demographic and macroeconomic assumptions as the Reference scenario […]*"

In European scenarios, or EU Member States scenarios, growth is always assumed to be greater than 1 %. For world scenarios, growth is also assumed to be positive on the long run, but with higher rates due to a larger growth in developing countries (such as in (Greenpeace, 2015; IIASA, 2012)).

Given the way GDP hypotheses are selected, or built, they are collectively very homogenous, in terms of values and trends (stable growth of roughly the same rates for all scenarios). However, growth is not as stable as demography, hence such a unity can be questioned. No scenario seriously considers the question of very low to negative GDP growth. This represents a collective blind spot for future studies, insofar that such negative trends for GDP may not be impossible.

GDP is used as a global constraint on the economic system in simulated agent models. In other words, the GDP hypothesis represents how much the economy will grow in the scenario. The GDP hypothesis ensures a consistency between consumption (in monetary value) and production (in monetary value) in the scenario, representing the global ability to produce goods and services on the geographical perimeter. Hence the GDP hypothesis translates hypotheses about:

- Geopolitics of the world, such as the relative economic power of different countries: The usual hypothesis is that of slowly changing geopolitical situations. No geopolitical crisis is assumed, which might be considered as a collective blind spot for future studies.

- Hypotheses about the financial sector and its possible crises: The usual hypothesis is that no more crisis will happen during the scenario timeframe. Theoretically, the reverse hypothesis could also be selected for some scenarios in order to think such a possibility.
- Planetary boundaries, such as the feedback effect of climate change on the economy, or the possible effects of peak oil in the scenario geographical perimeter: The usual hypothesis of a steady growth implicitly assumes that planetary boundaries are not significant determinants of the global economy during the scenario timeframe. This is largely questionable for "reference" scenarios leading to a significant climate change.

All these underlying hypotheses are largely unspoken. Detailing them leads to question the unity of GDP hypotheses across future studies.

Recommendations for scenario producers

A scenario strategy about GDP should be defined and justified. It should include considerations on the decision to study this subject or not. This choice depends on the Planning Question and on the study overall strategy. In case the subject is studied, the different aspects of it which are considered should be reported, and their links to the study strategy should be outlined.

Hereunder are aspects of GDP which may be reported about.

- Status of GDP in the scenario building: is it a driver of the whole scenario process (exogenous variable), or one of its results (endogenous variable)?
- Evolution of the GDP for each considered scenario
- Considerations on the differences (or absence of difference) between GDP evolutions across scenarios
- Positioning of the adopted hypothesis relative to other studies using a GDP hypothesis as a boundary condition: *is it a "usual" hypothesis for future studies? Does the scenario test a new style of GDP hypothesis?*
- In case GDP is exogenous:
    - reasons why such an evolution was selected for each considered scenario
    - narrative substantiating the described evolution: *why does GDP evolves this way? Under what drivers?*
    - considerations on the sensitivity of results to GDP: *how would results be different if GDP stagnates, or decreases in the scenarios?*

7. A very low diversity of assumptions about imported fuel prices

For European scenarios, (imported) fuel prices are considered as boundary conditions as the EU has no impact on them. Data about their evolutions usually come from selected databases produced thanks to world commodity models (such as the World Energy Model by IEA, PROMETHEUS by E3M, DECC 2050 Calculator by the UK Department of Energy and Climate Change). In some scenarios, a storyline is provided to explain prices evolutions. In other scenarios, they are considered as uncontrollable uncertainties, subject to sensitivity analyses.

For example, (European Commission, 2011) produced its assumptions on fuel prices through a world energy model called PROMETHEUS. Two sets of fuel prices assumptions are proposed, each associated with a different storyline about world evolution. PROMETHEUS incorporates assumption about global energy demand, resources and reserves, extraction costs and bilateral trade between regions. (European Commission, 2016) provides a detailed storyline supporting its assumptions for oil, coal and gas prices evolutions, also generated by PROMETHEUS model.

Many studies use World Energy Outlook (WEO) fuel prices projections for at least one of their scenarios (DGEC/CGDD/ADEME, 2015; Greenpeace, 2015; RTE, 2017; WWF, 2011). The methodology used by IEA to come up with fuel prices is based on a storyline of the world energy demand evolution matching a storyline about world supply system and resources availability. Storylines are different for the 3 scenarios proposed in the WEO.

Those prices are key drivers of the ES as they partly determine demand structure (consumption level, demand side technology mix, final energy carrier) and the power system supply-side (through shifts within different fuels to produce power).

Those prices evolutions all share common patterns: prices are not volatile at all, and they steadily increase during the scenario timeframe (except in the WEO's Sustainable Development Scenario, in which a high worldwide carbon tax is implemented and no more subsidies to fossil fuels exist except in a few countries).This leads to two consequences: the diversity of the fuel prices trajectories across scenarios is low, and the trajectories are not representative of the volatility which has been observed in the past.

Recommendations for scenario producers

Scenario producers should make the source of their hypotheses about fuel prices explicit, and they should substantiate their trajectory choices. They should provide a quick summary of the storyline accounting for each trajectory.

8. Industrial offshoring pattern and industrial activity increase

a. Industrial trends have various important impacts on the energy transition

Industry represents a significant part of energy, and electricity demand in EU. On the long run, offshoring patterns can significantly affect the energy and electricity system. They also affect the various impacts of the energy transition:

- Employment structure is obviously impacted when an activity is offshored (a need for labor force disappears) or re-shored (new need for labor force).
- Costs of technologies used in the scenario may be impacted by offshoring/re-shoring patterns, depending on the differences in wages levels in the considered countries. For example, if an industry producing a technology is offshored in a lower wages country, then the corresponding imported technologies are less expensive than technologies which were produced on-shore. In other words, offshoring patterns can lead to changes in technology prices, e.g. through using cheaper labor in less developed countries. This applies both for demand-side and supply-side technologies. However, to our knowledge no scenario makes such explicit assumptions. The evolution of technologies costs are usually exogenous hypotheses in scenarios, based on learning rates projections or expert judgement, as explained previously.
- GHG emissions[5] associated with production processes spatially follow these processes when they are offshored: if steel production is offshored, then its GHG impacts are also offshored. This reduces the GHG emissions impact of the considered territory, but might increase or decrease the GHG impact at world scale. E.g, if the offshored activity is more carbon-efficient than when it was on-shore then the global impact is reduced (and the other way round) (Barton et al., 2018).

b. Past trends are little considered in industry activity assumptions, and no storyline is provided to account for trend discontinuities

Some scenarios explicitly talk about industry offshoring or re-shoring:

For France, (Association négaWatt, 2014) assumes that all French end-consumption is produced on the French territory, which impacts supply-side design, GHG emissions and employment (however, the employment impact assessment performed does not take into account this re-shoring pattern (Quirion, 2013)). This approach leads to a GHG impact assessment which is equivalent to a footprint approach (see section on impact assessment).

[5] Or other environmental or society impacts

(Association négaWatt, 2017) makes a different assumption: it keeps steady ratios of imports and exports over end-consumption for each type of goods/materials.

(Barton et al., 2013) reports the changes in industry activity level leading to importation levels changes. They assumes for several UK scenarios a steep decline in energy intensive industry at the expense of more imports, subsequently to energy and carbon prices increases. This effect decreases the territory GHG impact assessment but not necessarily its carbon footprint.

Many scenarios are less explicit about offshoring / reshoring patterns because their main hypothesis about demand in industry is GDP evolution. (RTE, 2017) assumes different trends in industry production, which are globally higher than current trends. (European Commission, 2011; European Commission, 2016) both assume an increase in industry activity, hence probably an industrial development in EU.

In most cases, scenarios do not provide explanations in their storylines about trend discontinuity in industrial activity. However, the industry sector is very slow to change, in terms of physical infrastructures, which are long-lived[6], but also in terms of employees' skills and training. Also, industries evolve in an economic and institutional frame. Trend discontinuity in industrial activity might not be compatible with this frame. For example, relocation patterns in France may not be consistent with free movement of goods and capital between France and less developed countries.

Recommendations to scenario producers

Scenarios should be clear about their industry relocation hypotheses. The following aspects may be considered:

- Trend discontinuity: if the industry offshoring or activity trend exhibits a sudden reversal (for example, a reindustrialization after ten years of offshoring), or trend discontinuity (e.g. offshoring patterns suddenly decrease), an explanation for this may be proposed: *does the economic and institutional frame driving industry behavior evolve in the scenario?*
- Inertia of change: *how fast does the industry sector evolve? Does this change imply sunk costs?*
- Social impacts of offshoring, especially in terms of transition desirability in the scenario geographical perimeter (also see section on desirability)
- Environmental impacts of offshoring: for example, offshoring may lead to actually greater GHG emissions if industrial processes outside the scenario geographical perimeter are more emissive. Such global impacts of offshoring or (re-shoring) should be made explicit in order to inform the consistency (or inconsistency) across future studies handling different regions. For example, if all national studies assume offshoring patterns, then they are not compatible taken together: no global impact assessment can be based on these studies.

D. Boundary conditions for the power system (PS)

In this section, we focus on the power system (PS) and detail its specific boundary conditions.

1. Interactions with other energy subsystems are mostly on the demand-side in scenarios

a. Two types of energy carrier shifts: demand-side and supply-side

The PS evolution depends on the evolutions of the other energy subsystems (supply and demand-side).

Energy needs outside the power system (space and water heating, cooling, energy for transport etc.) must be taken into account in order to include all the aspects of the problem. Similarly, the other energy carriers

[6] Industrial facilities can last 40 years (Shalizi & Lecocq, 2009).

aside from electricity should be considered, as well as the possible interconnections between networks and possible inter-conversions between energy carriers (especially storage) (Hache & Palle, 2019).

These interactions are very important in the final scale and design of the PS, especially when the main driver of the energy transition is decarbonizing, as opposed to fulfilling a steadily growing energy demand. In times of strong energy demand growth (such as the post-WWII period when power systems where developed in Europe), this growth can be easily translated into growth rates for each energy subsystem, without much considerations on the interactions between energy carriers. When the driver of the system is a cross-carrier constraint such as decarbonizing, then the interactions between carriers are key for the sizing of each subsystem.

Interactions can be separated into two types of interactions:

- Supply-side interactions between carriers: these interactions consist in adaptations of the energy system's supply-side to convert one carrier into another. Examples include Power to H2 through hydrolysis or Power-to-gas through hydrolysis and Sabatier reaction.
- Demand-side (indirect) interactions between carriers, through shifts between technologies using different carriers for fulfilling the same service. Examples include the shift from ICE cars to electric cars, or from gas heating systems to power heating systems.

These evolutions can be better understood as a carrier match between energy system supply-side and energy system demand-side. In other words, demand-side technology share, corresponding to a demand-side carrier share, must correspond to the supply-side final carrier share (see section on demand).

Recommendations to scenario producers

Scenario producers should ensure consistency during the scenario timeframe between energy supply-side and energy demand-side systems, for each energy carrier.

Utilization of Sankey diagrams, or input/output matrices can be useful.

Consistency between the sector scope of the study, the evolutions proposed in the scenario and the driving questions should be substantiated. *For example, if a scenario proposes that mobility mainly switches to gas carriers and if the aim of the study is to assess the impacts of this change, then the study's sector scope should include the gas system.*

b. Demand-side: numerous technologies to shift between energy carriers but most scenarios assume demand shifts towards electricity

Several levers act on demand level and on the demand-side energy carrier share. Section on demand describes the different levers on the energy demand-side system (demand sobriety, technical and organizational sobriety, technology share, load rate and energy efficiency).

We focus here on the demand-side interactions between the power system and other energy subsystems. This corresponds to all the demand-side technology shifts leading to a switch between electricity and another carrier.

Scenarios make similar assumptions about these shifts:

- All transformational scenarios assume technology shifts within space heating systems, toward greater electrification: For France, (Association négaWatt, 2014) assumes a shift from heating systems based on oil or electric heaters to heating systems running on wood, electric heat pumps, micro CHP gas, district heat or thermal sun. (RTE, 2017) assumes a shift from oil to heat pumps. For UK, (Barton et al., 2013) assume a massive development of heat pumps. Similarly, for EU, (European Commission, 2011) assumes a greater electrification of space heating. For water heating, it proposes shifts from gas boilers and resistance heaters to heat pump heaters or thermal sun heaters.

- Similarly, all scenarios assume technology shifts within the mobility sector (more commonly called mode shift), from ICE car to lower carbon modes (public transportation, bike…) or to hybrid car, electric car, CNG/LNG car and so on. Most often scenarios assume a shift towards electric car, but a few exceptions exist ((Association négaWatt, 2014) propose a massive shift toward CNG/LNG cars).
- Some scenarios make assumptions about technology shifts within the industry sector, usually from heat processes (for compression or heating) to electric processes (Association négaWatt, 2014; RTE, 2017).

Many shifts can be imagined. For each energy service, PRIMES model documentation provides a list of technologies and the associated vector (E3MLab, 2017).

These shifts impact the long term evolution of the power system both through different energy needs during the year and through different power load patterns (the power at peak demand, or the time and duration of peak demand may evolve). For example, the electrification of mobility may lead to significantly greater peak demand depending on the management of the charging of batteries (RTE, 2017; Véronique Beillan, Caroline Bono, Sophie Bouly De Lesdain, & Fabien Bricault, 2018).

Recommendations to scenario producers

Scenario producers should describe the evolution of the carrier share and total demand on the demand side, through technology uses evolutions.

This evolution should be described in terms of annual energy amount and in terms of instantaneous power demand: *does peak demand evolve?*

c. Supply side: a few tools to go from power to other energy carriers, used sparingly in scenarios due to uncertainties on their economic viability

The supply-side of each energy subsystem on a given territory is composed of the following elements:

i. extraction industry and technologies to extract primary energy from the environment (hydropower, PV, wind turbines, biomass production, fossil fuels extractive industries, uranium mining industry, geothermal power plants, geothermal heat…),
ii. transformation technologies to convert one carrier into another (thermal power plants, power to gas technologies, coal to liquid fuels technologies etc), of into several others (Combined Heat and Power plants…),
iii. imports or exports of different carriers.

Supply-side interactions are included in point (ii). For the power system they are transformations from one carrier to electricity (that is, usual power plants, which are handled in the technology section) and transformation from electricity to another carrier. The latter category includes power-to-hydrogen, and power-to-gas.

Power-to-hydrogen and power-to-gas technologies are actually applied in a sequence, with the following processes:

- Hydrolysis is performed to convert power into chemical energy stored under the hydrogen (H_2) form, through decomposing water. H_2 can be directly used by industry, or by fuel cell cars, or it can be stored and converted back into electricity via a fuel cell later (in this case H_2 is used as an electricity storage technology). Finally, it can be injected in the natural gas network (up to 30 % of the gas volume, representing 20% of the energy) and burnt with natural gas.

- Synthetic methane (CH_4) is obtained starting from H_2 and making it react with carbon atoms from carbon dioxide (CO_2) through Sabatier reaction. The obtained methane can be totally incorporated to natural gas. CO_2 can be obtained from CCS or from biogas purification.

Hydrogen plays a more or less important role in scenarios depending on time horizon, type of power mix and economic hypotheses.

Some scenarios give an extensive role to hydrogen, which totally replaces natural gas (Greenpeace, 2015). In other scenarios, hydrogen plays a power storage role (ADEME, 2015). (European Commission, 2011) uses it to feed the natural gas network and as a storage technology. Similarly, (SFEN, 2018) assumes the emergence of H2 production from hydrolysis on the long-term (from 2050 to 2070), for injection in gas network and as a storage technology.

(RTE, 2017) points out that hydrolysers are currently heavy investments so they need a steady power supply in order to be bankable.

Other technologies or techniques to convert power into other energy carriers are mentioned by (Véronique Beillan et al., 2018), under the P2X concept. P2X is the set of processes to convert power into another energy carrier which can be stored: power to heat (P2H), power to gas (P2G), power to fuel (P2F), power to product (P2P), or product to liquid (P2L).

The overarching concept of P2X is to use power opportunistically to convert it into other products which can be reinjected in the energy chain. This reinjection can be either to produce power at another time, or to use X directly as an energy carrier. P2X is a way to benefit from the interactions between energy subsystems so as to use excess power production, for example when electric VRES production is higher than electricity demand.

P2X enables energy storage over seasons or weeks, which would turn useful for power mixes with high VRES share. However, some specific storage, and network infrastructure may be required. Plus, the economic viability of such technologies is still uncertain and depends on the scenario storyline.

Recommendations to scenario producers

The technologies used to transform electricity into other carriers should be described, in terms of technical characteristics, costs etc. The expected evolutions of these technologies should be detailed as should be the reasons for these evolution.

2. Interactions with neighbor power systems

The considered PS can be connected to other PSs through interconnections. Interconnections participate in the power supply balance at any time by bringing more power (imports) or by evacuating extra power (exports). Hence hypotheses about interconnections are important to understand the balancing capacity which will be available from interconnections in scenarios (this aspect is handled in operation section).

a. Interconnections: between solidarity and sovereignty

Some scenarios consider that the PS they propose should properly operate independently of the presence of neighbor PS (Association négaWatt, 2014; Association négaWatt, 2017; ECF, 2010). As such, they propose a supply-side which is sized as if it was operating independently from neighbor PSs. They assume that the situation with no interconnection at all with neighboring regions would represent a worst case situation. In their views, actual interconnections would bring more flexibility to the system. Their methodological choice is also based on the difficulty to propose a proper storyline about the long-term evolution of neighbor PSs. In a word, the underlying assumption is that of sovereignty of the different regions to control their own PS.

Other scenarios make assumptions about how the power mix in neighboring regions evolve, including for the French case pathways which might pose greater constraints for the French PS to ensure global security of supply than if no interconnection was available (RTE, 2017). This rationale assumes solidarity with neighbor regions.

b. Simulating interconnections requires assumptions about interconnection capacities…

The scenarios simulating interconnections define hypotheses to compute the evolution of the interconnection capacities[7] and sometimes the implementation of new interconnection links. Here are the different approaches we observed among future studies to simulate the long-term evolution of power system interconnections, from the most rudimentary to the most complex.

(ADEME, 2014) directly assumes an extra power capacity always available in case of need to import, or export, power, through an aggregate capacity of interconnection.

Some scenarios use results from inter-regional studies forecasting the evolution of interconnections in the considered region. Some handle the uncertainty about interconnection evolution through sensitivity analyses. For example, (RTE, 2017)'s hypotheses are based on results of public studies about the evolution of the EU interconnections.

Some other scenarios endogenize these hypotheses by modeling interconnections as market actors deciding to invest in new interconnection capacities. These actors decide depending on the benefits they can make following their expectation for internal rate of return (E3MLab, 2017).

c. … but also about neighbor PSs' long-term evolution and near-term operation

Defining the evolution of the neighbor PSs enables to simulate the interaction behaviors between the interconnected PSs: which PS needs to import and which needs to export, and at what times? Several approaches are used by future studies to simulate them.

As mentioned, (ADEME, 2014) assumes an extra power capacity always available in case of need to import, or export, power. However, this availability is assumed rather than checked through a modeling of, or assumptions about, the long-term evolution of the neighbor PSs.

(ADEME, 2015) considers five regions interconnected with the French PS and assumes an 80% RES mixes for those interconnected regions. (ADEME / Artelys, 2019) considers the rest of the European PS as evolving as described in the Ten Year New Development Plan 2018 from ENTSO-E. In those cases, studies assume as boundary conditions the evolution of interconnected PSs.

Scenarios using PRIMES model for the European energy system make implicit assumptions about interconnected PSs in Switzerland, Norway and the Balkans, even though they are not part of the modeled energy market (E3MLab, 2017; European Commission, 2011; European Commission, 2016; SFEN, 2018). In PRIMES, from the point of view of each EU Member State, the mixes of neighboring countries are co-developed in an integrated way through market mechanisms.

(RTE, 2017; RTE, 2018) assume three different pathways for the mixes in neighboring regions, including pathways which might pose greater constraints for the French PS to ensure global security of supply. Those pathways each integrate the interconnected regions into an economic model ensuring bankability of the different power generation technologies development.

In order to check the proper infra-day (hour by hour) operation of the interconnected PSs, some scenarios use climate models of the different regions which properly represent the correlations between weather patterns across regions. For example, wind patterns, or sunlight patterns are somewhat correlated across European countries (Véronique Beillan et al., 2018). Similarly, they use demand models which also represent correlations between the different demand patterns which are due to outside temperature, weather, or time of the day (ADEME, 2015; RTE, 2017).

[7] The capacity of the interconnection represents the amount of instant power which can be transported in the interconnection line.

d. Impacts measured through interconnections

In scenarios in which the PS is interconnected with neighbor regions, electricity imports and/or exports may be significant. This raises the question of how to assess the impact of those imports and exports.

As described in the Impact Assessment section, the assessment perimeter may be the descriptive perimeter, in which case no account of imports or exports are considered in the various impact assessments. However, if the assessment perimeter is of a footprint type, then the impacts associated with imports are counted in the assessment whereas the impacts associated with exports are counted out (RTE, 2017). These impacts can be assessed on an hour by hour basis, or finer time step, in order to account for the different types of power plants operating at each time step if this has an importance for the assessment (such as the costs of production of the different plants, or their carbon emissions).

This can be done for any type of assessment (such as economic assessment, or CO_2 emissions assessment).

Recommendations for scenario producers

A scenario strategy about interconnections should be defined and justified. It should include considerations on the decision to study this subject or not. In case interconnections are studied, the different aspects which are considered should be reported, and their links to the study strategy should be outlined.

Hereunder are aspects of interconnections which may be reported about. Questions in italic are examples to illustrate the aspects which are dealt with.

- Hypothesis of sovereignty or solidarity. This hypothesis should be substantiated, especially if it requires evolutions from start year situation (e.g. currently interconnected power systems which go independant). *Is the studied PS independent of other, neighboring PSs? Is it fully connected to neighboring PSs with no means to control the interconnections?*
- Interconnected power systems and their evolutions: *which regions are interconnected? How do the neighboring PSs evolve during the scenario timeframe? Why do they evolve in such a way?*
- Interconnection lines capacity: *how does the interconnection capacity evolve during the scenario timeframe? Are new lines created?*
- Demand and supply instantaneous behavior of neighbor PSs. *Specifically, for scenarios in which neighboring regions have large shares of VRES, which method has been used to simulate the supply of these regions?*
- Impacts: the strategy to integrate impacts associated with power imports/exports in the results, for each impact which is considered in the study (e.g, GHG emissions), or a substantiation for not taking them into account) should be described.

Bibliography

ADEME. (2012). *L'exercice de prospective de l'ADEME - « Vision 2030-2050 »*.

ADEME. (2014). *Visions énergie climat 2030/2050 - Quels modes de vie pour demain ?* (Nº 8102; p. 132).

ADEME. (2015). *Un mix électrique 100% renouvelable ? Analyses et optimisations*.

ADEME / Artelys. (2018). *Trajectoires d'évolution du mix électrique 2020-2060 - Synthèse*.

ADEME / Artelys. (2019). *Trajectoires d'évolution du mix électrique 2020-2060 - Foire aux questions* (p. 30).

ANCRE. (2013). *Scénarios de l'ANCRE pour la transition énergétique*.

Association négaWatt. (2014). *Scénario négaWatt 2011-2050 - Hypothèses et méthode*.

Association négaWatt. (2017). *Scénario négaWatt 2017-2050 | Dossier de synthèse* (p. 48).

Barton, J., Davies, L., Dooley, B., Foxon, T. J., Galloway, S., Hammond, G. P., … Thomson, M. (2018). Transition pathways for a UK low-carbon electricity system: Comparing scenarios and technology implications. *Renewable and Sustainable Energy Reviews*, *82*, 2779‑2790. https://doi.org/10.1016/j.rser.2017.10.007

Barton, J., Huang, S., Infield, D., Leach, M., Ogunkunle, D., Torriti, J., & Thomson, M. (2013). The evolution of electricity demand and the role for demand side participation, in buildings and transport. *Energy Policy*, *52*, 85‑102. https://doi.org/10.1016/j.enpol.2012.08.040

Bovari, E., Giraud, G., & Mc Isaac, F. (2018). Coping With Collapse: A Stock-Flow Consistent Monetary Macrodynamics of Global Warming. *Ecological Economics*, *147*, 383‑398. https://doi.org/10.1016/j.ecolecon.2018.01.034

DGEC/CGDD/ADEME. (2015). *Scénarios prospectifs Energie - Climat - Air pour la France à l'horizon 2035*.

Donella H. Meadows, Randers, J., & Meadows, D. L. (2004). *Limits to growth: The 30-Year Update*. Chelsea Green Publishing; 3 edition (June 1, 2004).

E3MLab. (2017). *PRIMES Model, Version 6, 2016-2017 - Detailed model description*.

E3MLab & IIASA. (2016). *Technical report on Member State results of the EUCO policy scenarios* (p. 381).

ECF. (2010). *Roadmap 2050 - A Practical Guide to a Posperous, Low-Carbon Europe*.

European Commission. (2011). *Energy Roadmap 2050 - Impact assessment and scenario analysis*.

European Commission. (2016). *EU reference scenario 2016: energy, transport and GHG emissions : trends to 2050.* Luxembourg.

Fraunhofer ISE. (2015). *What will the energy transformation cost? - Pathways for transforming the German energy system by 2050*.

Greenpeace. (2015). *Energy [R]evolution - A sustainable world energy outlook 2015* (p. 364).

Hache, E., & Palle, A. (2019). Renewable energy source integration into power networks, research trends and policy implications: A bibliometric and research actors survey analysis. *Energy Policy*, *124*, 23-35. https://doi.org/10.1016/j.enpol.2018.09.036

IIASA. (2012). Energy Pathways for Sustainable Development. In *Global Energy Assessment Towards a Sustainable Future*.

International Energy Agency. (2017). *World Energy Model Documentation - 2017 Version* (p. 77).

International Energy Agency. (2018). *World Energy Model Documentation - 2018 Version* (p. 82).

Lappeenranta University of Technology / Energy Watch Group. (2017). *Global energy system based on 100% renewable energy - Power sector*.

OECD/IEA. (2017). *World Energy Outlook 2017* (p. 782).

OECD/IEA. (2018). *World Energy Outlook 2018* (p. 661).

Quirion, P. (2013). *L'effet net sur l'emploi de la transition énergétique en France : Une analyse input-output du scénario négaWatt*.

RTE. (2017). *Bilan prévisionnel de l'équilibre offre-demande d'électricité en France*.

RTE. (2018). *Bilan prévisionnel de l'équilibre offre-demand d'électricité en France - Synthèse* (p. 36).

Samadi, S., Gröne, M.-C., Schneidewind, U., Luhmann, H.-J., Venjakob, J., & Best, B. (2017). Sufficiency in energy scenario studies: Taking the potential benefits of lifestyle changes into account. *Technological Forecasting and Social Change*, *124*, 126-134. https://doi.org/10.1016/j.techfore.2016.09.013

SFEN. (2018). *Le nucléaire français dans le système énergétique européen*.

Shalizi, Z., & Lecocq, F. (2009). *Climate Change And The Economics Of Targeted Mitigation In Sectors With Long-Lived Capital Stock*. https://doi.org/10.1596/1813-9450-5063

The University of Cambridge Institute for Sustainability Leadership / Kering. (2017). *Linking planetary boundaries to business* (p. 18).

Véronique Beillan, Caroline Bono, Sophie Bouly De Lesdain, & Fabien Bricault. (2018). *Les systèmes électriques de demain - Un défi pour la transition énergétique*. Tec & Doc Lavoisier.

WWF. (2011). *The Energy Report - 100% renewable energy by 2050*.

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The Shift Project

The Shift Project, a non-profit organization, is a French think-tank dedicated to informing and influencing the debate on energy transition in Europe. The Shift Project is supported by European companies that want to make the energy transition their strategic priority & by French public funding.

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Long-term evolution of energy consumption in energy transition scenarios

Technical file #4 – Draft version

Information and recommendations for scenario producers

This document is part of a set of 12 technical files. These files have been produced by *The Shift Project* after one year and a half of research and experts consultations on the different aspects of energy transition and the future studies around these aspects.

Our project, "Power Systems 2050 – Guidelines for design," started in January 2018, with the participation of 10 experts who defined the key subjects which according to them have to be collectively tackled by future studies about the power transition. *The Shift Project* then investigated each of these subjects, consulting in total 40 experts, organizing 4 workshops, and reviewing a large bibliography, including a dozen of future studies about power (and energy) transition at different geographical scales.

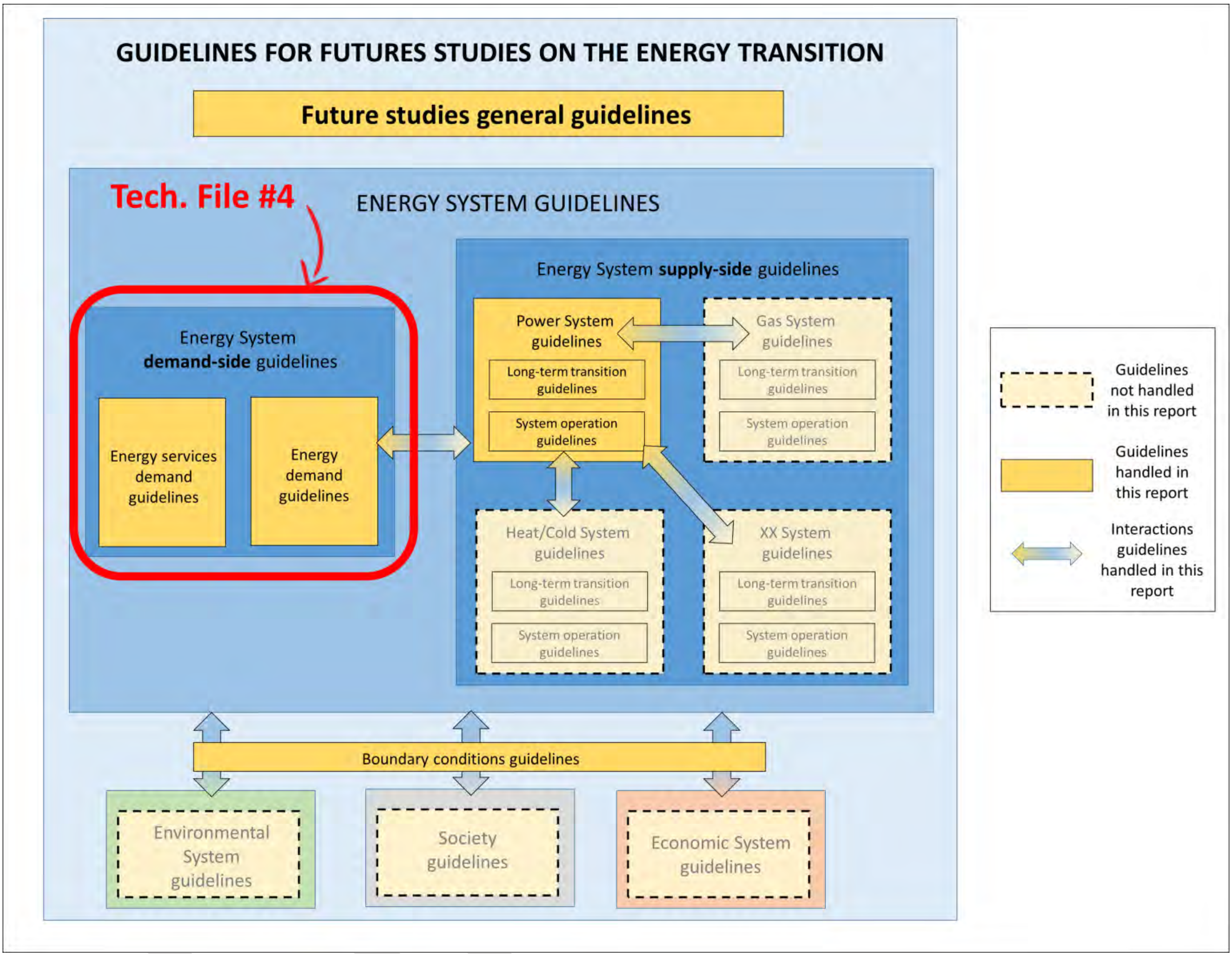
The goal of this project is to produce a set of guidelines addressed to scenario producers. These guidelines seek to foster transparency and consistency *within* future studies and to develop a common language *across* studies. By defining a number of important items which are key to deal with in future studies, we actually propose a study template which enables a better understanding of the location of each proposed scenario on the tree of possible transitions. Once again, the objective is not to *rank* studies, or scenarios, but rather to *compare* them to get a better collective overview of the different aspects of the transition (what are the differences between studies in terms of driving questions, hypotheses, models, methodology, results?).

Several aspects of the energy transition are handled in these technical files. However, on the energy supply-side only the power system has been studied. The main reason for this choice is that we had to start from somewhere with limited resources, and the power system seemed to be a key system to study in the energy transition context, towards a low-carbon economy, as shown by the growing number of future studies focusing on this system. However, the guidelines we propose could be completed by analyzes on the other energy supply-side systems (the gas system, oil system, heat system and so on).

Each technical file tackles several aspects of future studies for the power (and energy) transition. Here is the complete list of the technical files produced during the project:

#	Technical file title
1	Future studies on the energy transition
2	Energy transition models
3	Boundary conditions for energy transition scenarios
4	Long-term evolution of energy consumption in energy transition scenarios
5	Lifestyles and consumption behaviors in energy transition scenarios
6	Long-term evolution of the power system supply-side in energy transition scenarios
7	Power system operation in energy transition scenarios
8	Impact assessment in energy transition scenarios
9	Transition desirability in energy transition scenarios
10	Environmental assessment of energy transition scenarios
11	Economic evaluation of energy transition scenarios
12	Employment assessment of energy transition scenarios

Altogether, these files cover the fields described on the following map of the guidelines for future studies on the energy transition. The document you are reading covers the red-circled topics.



In addition to these technical files, three complementary notes have been produced as specific focuses on the following aspects: material criticality in energy transitions (in French, to be translated and added to technical file #10), levelized cost of electricity (LCOE) in energy transition future studies (in French) and discount rate in energy transition future studies (in French).

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Table of content

Reading keys

Explanation box, containing key information for a better overall understanding of the subjects.

Recommendations to scenario producers:

These boxes contain the recommendations for scenario producers.

The word "should" means that scenario producers, if they are to follow the guidelines, must substantiate the corresponding point. The words "may" or "might" relates to suggestions, ideas to help the scenario producer respond to the point.

Questions in italic are examples of questions scenario producers might ask to substantiate the points. They are here in an illustration purpose.

Phrases in italic relate to words which are being defined and will be subsequently used in the framework.

Phrases which are highlighted in yellow refer to other technical documents of this series.

A. Introduction

This chapter tackles the long-term evolution of energy consumption, as opposed to hour per hour evolution. In other words, we consider here the long-term drivers of energy consumption. As a consequence, energy consumption is talked about in this section in terms of total yearly consumption rather than instant power consumption.

1. The traps of energy accounting

Energy comes in different forms, each having different uses. These forms are commonly called *energy sources* or *energy carriers*. An energy carrier is produced from an energy source (for example, electricity produced from coal combustion), and is then used for an end-use (e.g. electricity consumed in an electric engine to get mechanical energy) or is used to produce another carrier (e.g., electricity consumed to fill an electric battery as chemical energy).

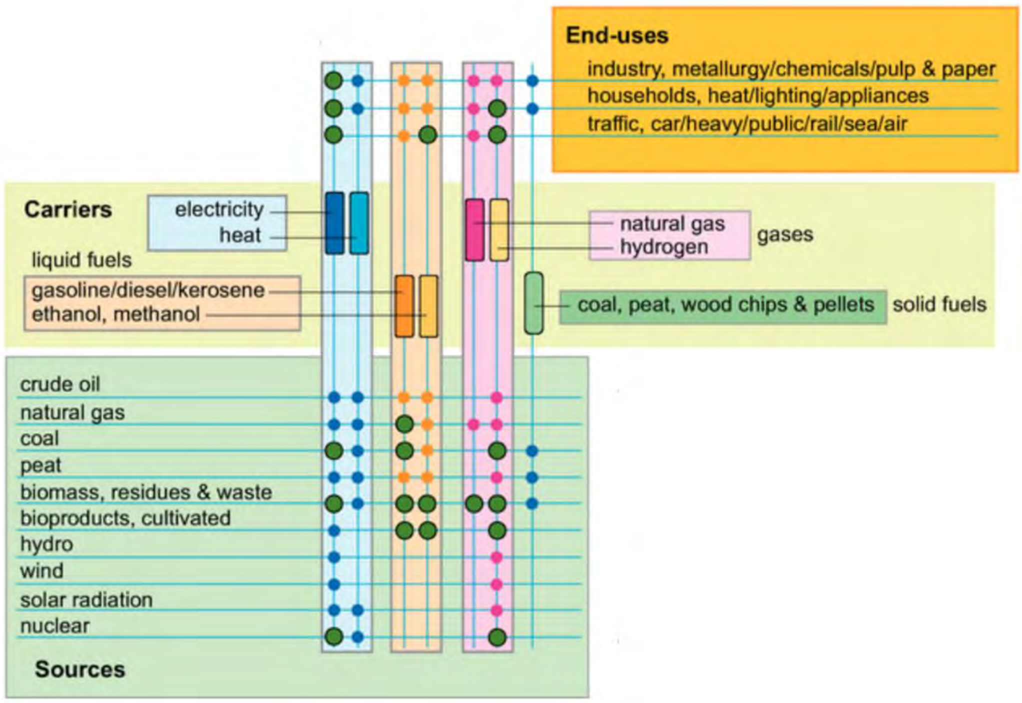

Figure 1: Dynamic interplay between energy sources, energy carriers and energy end-uses. Source: (IPCC, 2007)

These forms have different uses, hence they are not equal in practical terms. For example, petroleum is useless to power a TV set, and electricity is useless to power an internal combustion engine (ICE) car.

However, representing all the carriers on one graph can help figuring out use ratios between different carriers, for example showing the dependence level of a country to such or such carrier. This is why methods to account energy under its different forms have been developed.

Here are some methods used to account energy:

The partial substitution method:

When accounting energy under its fuels and electricity forms (for example, when accounting primary energy, including different fuels and renewables), this method converts electricity produced from renewables into the oil energy amount that would be required to produce an equivalent amount of electricity in a standard power plant (about 40% conversion efficiency). In other words, if 1 MWh of electricity is produced by a PV panel, it will be accounted as 2.5 MWh of energy[1]. Other fuels are accounted as their heat value. For example, if 2.5 MWh of oil is

[1] Indeed, 2.5 MWh of energy from oil combustion (heat) would produce 2.5*40 % = 1.0 MWh of electricity.

consumed in a car, it will be accounted as 2.5 MWh of energy. Similarly if these 2.5 MWh of oil are used to produce 1 MWh of electricity, the energy dissipated by oil will be accounted as 2.5 MWh of energy.

The physical energy content method:

This method defines a "primary" form for each form of energy, and accounts the amount of energy under this primary form. Usually, the primary energy form associated with nuclear is heat. With this method, accounting for an amount of electricity produced from nuclear reaction is equivalent to accounting the heat dissipated by the reaction in order to produce that electricity. The average energy conversion efficiency of nuclear power plants being 33 %, if 1MWh of electricity is produced from nuclear, then it will be accounted as 3 MWh of energy from nuclear[2]. For hydropower, or PV power, the associated primary energy is directly electricity; as a result, these energies are accounted as after their conversion into electricity (that is, if 1 MWh of electricity is produced from PV, it will be accounted as 1 MWh of energy).

For fuels as coal, oil, gaz and biofuels, conversion is made using the heat value as in the example of nuclear. However, different heat values obtained through combustion can be accounted: high heat value (also called gross calorific value), or low heat value (also called net calorific value). Low heat value represents the heat obtained directly through the combustion; however, exhaust gases still contain hot vapor; high heat value, in addition to the low heat value, incorporates the energy contained in the exhaust vapor compared to liquid water. In practice, the amount of energy that can be collected from combustion corresponds to the low heat value. However, the greater the amount of moisture and of hydrogen content of a fuel, the greater the difference between its low heat value and its high heat value[3] (United Nations & Statistical Division, 2018).

The physical energy content method is usually preferred, because it requires no assumption about what is the preferred energy form in a technical system. The partial substitution method assumes, among others, that electricity has a higher value for society than oil (which produces high temperature heat). But there might be societies in which electricity is plenty whereas high temperature heat is scarce, for example societies mostly running on electric renewables (hydropower, PV, wind), and in which other forms of energy would be useful (such as kerosene for airplanes). In those societies, getting oil would be more difficult and would require to convert electricity to liquid fuels. Hence the partial substitution method may need to consider that 1 MWh of oil has to be accounted as 3 MWh of electricity (as processes to convert electricity into oil generate about 2/3 of losses) (David JC MacKay, 2009).

On the contrary, the physical energy content method would not need to be altered in such cases.

A usual effect of accounting following the physical energy content method is that going to more electric renewable energies in replacement of fossil fuels or nuclear in the power mix leads to a decrease in primary energy consumption, as if the energy conversion from raw, found-in-nature energy to electricity was getting more and more efficient (for example, going from 1 MWh of electricity from coal to 1 MWh of electricity from wind is equivalent to going from 3 MWh of coal primary energy to 1 MWh of wind primary energy). Indeed, this accounting method assumes electricity can be extracted from the environment through renewables with a total efficiency (Brown et al., 2018).

Recommendations to scenario producers

Scenario producers should make their energy accounting method explicit when they compare different carriers.

They should also make explicit their choice about heat conversion values (low vs high heat value) when they use heat as an accounting reference, and substantiate their choice.

2. In most scenarios, energy demand is the main driver of energy systems

Some studies consider that energy demand is the main driver of energy systems. This is typically the case of studies exploring options about the energy supply-side system, in which demand is defined exogenously, or quasi-

[2] Indeed, 3 MWh of energy (heat) from nuclear reaction produces 3.0*33 % = 1.0 MWh of electricity

[3] For example, high heat value of charcoal (very dry and very low hydrogen content) is 0 to 4 % higher than its low heat value; high heat value of fuelwood with a 40 % moisture content is 45 % higher than its low heat value.

exogenously (e.g. directly derived from GDP) and then an energy supply-side system is defined to fulfill the demand. In this view, demand drives and sizes the overall energy system (Riahi et al., 2012). We call these studies *technical studies*.

A few scenarios (especially local scenarios) use the reverse rationale: they start from local resources to define possible supply-side systems and deduce the required evolution of demand-side and of level of demand. Their underlying assumption is that of energy independence through local (and sustainable) extraction of energy. Under those assumptions, local resources drive (local) demand.

In reality, energy demand and the energy system co-evolve, influencing each other; it cannot be said that one entirely drives the other. Some studies represent this mutual influence through market models, clearing demand and supply offers while producing a price: we call these studies *partial equilibrium studies*. Under some conditions, this is equivalent to minimizing the total cost of the complete energy system (Loulou, 2016). But even in those cases, demand is often largely driven by exogenous variables (such as GDP and population hypotheses) whereas supply-side system is essentially driven by demand.

B. Current practices for assessing energy demand evolution

1. The different approaches to assess energy demand evolution have different strengths, but all lead to inconsistencies

Two main approaches are used to assess energy and electricity demand evolutions. We call the first approach "behavior-based", the second one being called "GDP-based". These approaches are described in the following subsections:

a. The behavior-based approach usefully informs the transition debate on some of its sociological aspects but requires in turn a good knowledge of the considered population habits

The behavior-based approach starts from the behaviors of economic agents in terms of energy services. This approach is used in (ADEME, 2014; Association négaWatt, 2014; Fraunhofer ISE, 2015). In this approach the storyline is about lifestyles, evolutions of energy services technologies and uses:

- hypotheses about how households will consume (sobriety, new uses or different uses, carrier shifts), and how energy services equipment (such as cars, fridges, or TV sets) will evolve in terms of energy efficiency, are derived from the storyline.
- For commercial and tertiary activities, hypotheses are made on the overall demand evolution for trade and services in the first place, and then on the evolution of energy services equipment in these sectors (such as heating systems, cooling devices for food storage, etc).
- For the industry sector, the global (domestic and foreign) demand for various commodities, industrial offshoring and inshoring behaviors and energy efficiency of production processes are the subjects on which the main hypotheses are made. During this step, some scenarios ensure a consistency between households' equipment consumption and industry production level, by posing hypotheses about place of goods production.

These hypotheses can be more or less aggregated along two dimensions:

- They can be much disaggregated at the energy service technology level. In other words, for a given service, a variety of technologies with different technical characteristics are described, such as different types of fridges characterized by their energy efficiency. Such disaggregation is often called "*technology-rich*."
- They can also be much disaggregated at the behavior level. In other words, a variety of different behaviors depending on social factors are included in the discussion, such as place of living, social category, family structure and so on. A rich set of different subpopulations is defined depending on their lifestyles. Such a disaggregation is called here "*lifestyle-rich.*"

Having defined those hypotheses, energy consumption is computed per carrier.

This approach is by nature much more lifestyle-rich than the GDP-based approach. Hence the scenarios can describe in a precise way how lifestyles evolve (for example (ADEME, 2014) describes the lifestyles associated with the Visions scenario (ADEME, 2012)). This transparency about lifestyles opens useful discussions with behavior scientists (such as sociologists, psychologists, historians…) and the greater public about the hypotheses, ensuring a greater consistency between the scenarios and behavior sciences results.

In this approach, the consistency is not ensured between industry production and the transition of the energy supply-side (such as building new power plants, a new grid architecture, etc., which may be capitalistic). Indeed, once industry demand is determined (along with other sectors' demands), a supply-side system is proposed to fulfill the resulting demand, but no feedback loop is implemented to take into account the fact the supply-side transition requires energy in industrial processes. This may be problematic for world scenarios, inasmuch their transition requires more capital, because in those cases a substantial amount of energy is dedicated to performing the transition (as opposed to running the usual economy), as shown by (Bouneau, 2018). For regional scenarios, this approach may hide significant impacts on trade balance for transformational scenarios (as high capital transition may require lots of imports).

In this approach, a macroeconomic view can be brought afterwards through models soft-linking[4]: for example, ADEME used the ThreeMe model to deduce GDP evolution and jobs evolutions from consumption hypotheses taken from their Vision scenarios (ADEME, 2012; ADEME, 2013) (see employment section).

b. The GDP-based approach is not rich enough to inform the sociological debate but can be applied on perimeters with a low knowledge of population's habits

The GDP-based approach starts from macroeconomic assumptions, such as assumptions on demographic trends and GDP trends. The storyline is about those indicators and why these assumptions have been selected (substantiation is often reduced to providing the source of data, which is considered as a reference, or to a short storyline – see section on boundary conditions). Scenarios built with PRIMES model, such as scenarios from the European Commission or from Société Française pour l'Energie Nucléaire (SFEN) (E3MLab & IIASA, 2016; European Commission, 2011; European Commission, 2016; SFEN, 2018), as well as scenarios built from POLES model (Keramidas, Kitous, Schmitz, European Commission, & Joint Research Centre, 2017) (scenario used for the French Stratégie Nationale Bas Carbone (DGEC/CGDD/ADEME, 2015; Ministère de l'écologie, du développement durable et de l'énergie, 2015)) follow this approach. The Global Energy Assessment (GEA) pathways (IIASA, 2012) also follow this approach to determine demand which is used as an input to MESSAGE model.

Some studies use this approach in a very simplified way, posing GDP assumptions and global energy efficiency assumptions to deduce the overall energy consumption level by 2050 (ECF, 2010). This is implicitly the approach used by (IIASA, 2012). The energy demand in Energy [R]evolution scenarios is based on dedicated studies (Graus & Kermeli, 2012; Greenpeace, 2012; Greenpeace, 2015), which use GDP evolution per country to frame their demand projections. In the three cases, the demand for a reference scenario is defined mostly from GDP projections, and then energy efficiency measures are imagined to deduce a low demand scenario.

This approach can be endogenized in models. In this case, GDP growth is used as an input to determine the evolution of global demand per sector, using assumptions on the structure of the economy. This structure can evolve based on different policy assumption.

Some models, such as POLES, use reduced forms equations (with demand elasticities as main parameters) directly linking GDP variation to energy demand variation for each sector (E3MLab, 2017).

Other models, as a first step, link "explanatory" variables such as GDP, to "activity" indicators such as vehicle-miles travelled. In a second step, they model consumption behaviors matching this activity, which determines energy consumption. This is the strategy adopted by PRIMES, which models consumption behaviors based on different available energy services technologies (such as cars, fridges, industrial processes…) and on optimal market choice

[4] Soft-linking refers to a modeling technique to couple two different, complementary models. The technique is to run each model iteratively, each one providing inputs to the other one, until convergence is reached for the different variables, which means a consistency point has been reached between both models (Krook-Riekkola, Berg, Ahlgren, & Söderholm, 2017).

simulations. In this case, GDP represents an overall consumption "envelope" which has to be consumed, but it does not directly determine how energy is consumed and under what carrier. This approach is technology-rich as it represents the different energy services technologies.

In both cases, energy demand per carrier is eventually determined.

A few physical inconsistencies can appear with such an approach based on monetary flows for energy commodities:

- consistency between industry production (as could be measured in tons of produced materials) and goods consumption by end-users (number of built objects, such as the number of cars required to ensure mobility in the scenario, and non-energy infrastructure, such as roads) is not ensured. As a result, the energy consumed by industrial processes may be inconsistent with the projected demand in goods in the scenario. This inconsistency comes from the very determination of energy demand in all the sectors from a common GDP hypothesis, as opposed to determining industry demand from end-consumer demand first (see Figure 2 and Figure 3). Goods' markets modelling could be a way to ensure this consistency, but they are not modelled in partial equilibrium models. Another way to see that no consistency is ensured is that modelled industrial processes have no consideration on material flows. Hence no consistency is ensured between, e.g., car production and the number of cars produced.

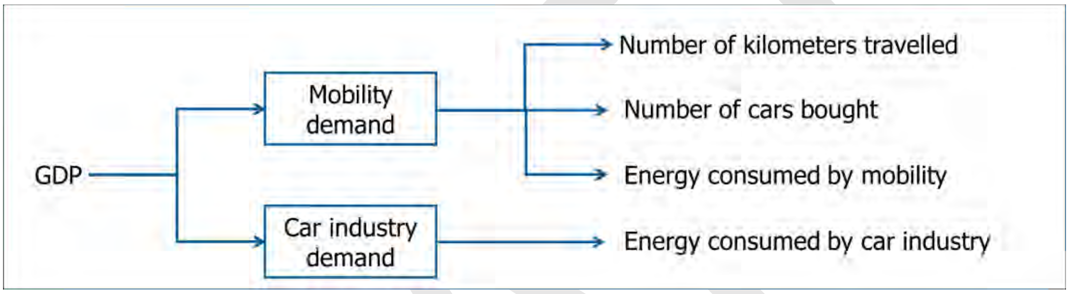

Figure 2: In the GDP-based approach, energy consumption is derived from GDP assumptions for each sector, including industrial sector. This approach ensures an economic consistency between the projected activity level of each sector and the global GDP. However, taking the example of car industry, consistency is not ensured between the number of cars bought, which have to be produced by car industry, and car industry demand.

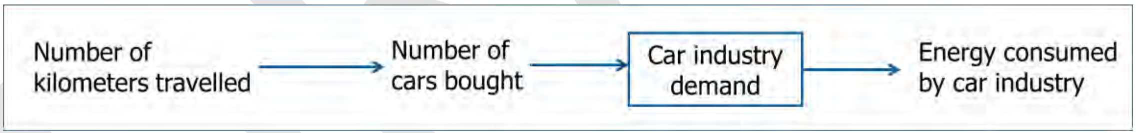

Figure 3: In the behavior-based approach, behaviors of end-consumers determine consumption of goods (cars), which in turn determine demands for industries (such as how many cars have to be produced by car industry). Demand for industry then determines energy consumption by industries.

- As for the behavior-based approach, consistency is not ensured neither between industry production and the transition of the energy supply-side (which, as already mentioned, may be capitalistic), for the same fundamental reasons: energy-infrastructure industry activity is determined by the GDP hypothesis as opposed to being determined by the sizing of the energy supply-side (that is, how many power plants or how many kilometers of high voltage lines to build). This may be problematic for world scenarios, inasmuch their transition requires more capital, because in those cases a substantial amount of energy is dedicated to performing the transition (as opposed to running the usual economy), as shown by (Bouneau, 2018). For regional scenarios, this approach may hide significant impacts on trade balance for transformational scenarios (as high capital transition may require lots of imports).

This approach is largely based, and calibrated, on observations of past economies, which can lead to inconsistencies for transformational scenarios. For example, consumers' preferences evolutions, or evolution of price-demand elasticities (representing relative choices evolution due to relative prices evolution) cannot be modelled, even for a transformational scenario. Hence some aspects of lifestyles evolution cannot be modelled (see section on lifestyles).

Furthermore, in this view, lifestyles (including employment structure) evolve totally fluently through market forces (which are themselves framed by policies). This may pose desirability issues for transformational scenarios (see section on desirability).

As a general rule, scenarios covering a large territory (such as world regions, or the world) use the GDP-based approach. Indeed, behavior-based approaches require a fine knowledge of population habits and of the heterogeneity of consumption behaviors depending on the subpopulations. Such data is more difficult to collect, and handle, for large territories modeling.

c. Hybrid approaches

Hybrid methods for power systems scenarios are sometimes used (ENTSOG/ENTSO-E, 2018; RTE, 2017), they define storylines about behaviors, technologies, vector shifts etc., but ensure their inner consistency through GDP hypotheses: e.g., the Bilan Prévisionnel from RTE (RTE, 2017) assumes that the energy efficiency is stronger in scenarios in which demand is greater because both are linked to a greater GDP.

d. Supply-side only approaches are used to inform about the possible evolutions of the power systems supply-side with an exogenously fixed demand

Finally, some future studies do not compute demand levels but reuse demand trajectories from other studies. For example, two studies from ADEME (ADEME, 2015; ADEME / Artelys, 2018) directly use power demand trajectories from other studies, as boundary conditions.

Usually, studies focusing on the supply-side of the energy system, or the power system, use the latter approach. In these studies, a supply-side system is modelled, demand being fixed beforehand. Hence no trade-off (would it be based on an economic criterion or any other criterion) can be performed between actions on the supply-side and actions on the demand-side (such as introducing energy efficient consumption devices, or shifting between technologies providing the same energy service)[5].

Recommendations to scenario producers

The scenario strategy about energy demand determination should be defined and justified.

Hereunder are aspects of energy demand determination which should be reported about.

- Approach which is adopted to determine energy demand level: GDP-based, behavior-based, hybrid, or direct demand reuse from another study. The reason why such an approach has been adopted.
- If the behavior-based, or hybrid approach has been adopted
  - Level of disaggregation of the end-use technologies may be described
  - Level of disaggregation of the subpopulation types should be described, e.g. per type of energy service use
  - Limitations induced by the approach, such as possible inconsistencies between supply-side evolution and energy demand due to the absence of feedback loop between them, should be described. Substantiation about the possible effects of these limitations on results should be provided.
- If the GDP-based approach has been adopted
  - The links between GDP and final energy demand should be made explicit and a qualitative substantiation should be provided for these links. *For example, how is activity level determined from the overall GDP? How does this link evolve through scenario timeframe, and why? Is the structure of the GDP share per sector assumed to evolve during the scenario timeframe?*

[5] For example, (ADEME / Artelys, 2018) compares the costs of a supply-side system designed to fulfill a low demand trajectory to the cost of a supply-side system designed to fulfill a high demand trajectory, without including in the cost assessment the costs related to the demand modifications between both trajectories. As a result, the cost comparison does not really hold any decision value towards a lower demand or a higher demand option.

How have demand price elasticities been calibrated, how and why do they evolve through the scenario?

- Limitations induced by the approach should be described, such as
  - possible inconsistencies between industry goods production and energy demand from industry along the scenario, or between supply-side evolution and energy demand, e.g. due to the absence of feedback loop between those aspects, should be described. Substantiation about the possible effects of these limitations on results should be provided.
  - Lifestyle evolution considerations, such as stiffness of consumers' preferences in a fast-, largely-evolving incentive context, or the fluency of job structure evolution. Substantiation about the possible effects of these limitations on results should be provided.

2. Two types of levers to reduce energy demand: energy efficiency and sobriety

"Sobriety consists in refraining from consuming energy by for instance staying home during the weekend instead of taking the car or by lowering the heating temperature in the house" (Reynès, Yeddir-Tamsamani, & Callonnec, 2011).

In a more consensual way, sobriety is sometimes referred as sufficiency.

"Sufficiency [...] addresses the "level" of output (or consumption) per se – and not in relation to the inputs (as technical efficiency does). It asks whether an activity needs to be performed at all (excess meat consumption, multiple car ownership, or extraordinarily high mobility service demand) and not whether it is performed "efficiently."" (Roy et al., 2012)

Some others talk about reducing the level of energy services demand by restructuring those energy services (such as substituting "physical" mobility by "digital" mobility through communication devices) or by organizing differently the context in which they take place (such as living closer to ones workplace to reduce mobility needs, or insulating one's house to reduce heating needs) (Riahi et al., 2012).

"Avoid, Shift, Improve" rationale is also useful to characterize energy demand transition. This an end-user rationale (The Shift Project, 2017). *Avoid* is close to sobriety (consume less of a service), or organizational efficiency (live closer to work to reduce travel, insulate house, substitute physical mobility with virtual mobility…); *shift* corresponds to carrier shift to provide the same energy service (e.g., shifting from a gas boiler to an electric boiler, from an oil ICE car to an electric car, or shifting from an oil ICE car to a muscle powered bike); *improve* is technological improvement within one carrier for the same service. *Improve* can gather two types of improvement: either using differently the same technology to get a better energy efficiency per unit of service (such as higher occupancy rate for cars, or smoother driving), or using a more efficient technology (such as a car consuming less energy in average).

C. A common frame to collectively think energy consumption and its evolutions through a behavior-based approach

In this section, we propose a simple and consistent frame and the associated terminology to help discussing about energy consumption evolution under a behavior-based approach. This frame is largely inspired by the various studies using this approach, such as (ADEME, 2014; Association négaWatt, 2014; Fraunhofer ISE, 2015).

The behavior-based approach is developed as it better informs the debate about demand evolution by providing details about what concretely changes in the behaviors and lifestyles. On the contrary, the GDP-based approach is of little use to collectively think and discuss behaviors generating energy consumption because it is not concrete enough on these aspects. Behaviors are a blind spot of the GDP-based approach.

1. Overview of the proposed behavior-based frame

Energy demand can be determined through a behavior-based approach starting from *human demand*. Human demand, as defined here, emerges from human needs like eating, being at a comfortable temperature, feeling clean, having clean laundry, having access to leisure and entertainment, to medication, etc, and its fulfillment involves energy consumption.

We call *energy-service system* the macro, aggregated system fulfilling a given type of human demand. Energy-service systems are produced to fulfill human demand by consuming different forms of energy. For example, the mobility system fulfills demand for people accessing activities; the laundry washing system fulfills demand for people having clean laundry, and so on. The definitions of such macro systems is subject to debate about their usefulness in each study's context: for instance it may be more relevant to distinguish, and define, a long-distance mobility system and a short-distance mobility system rather than an aggregate mobility system, depending on the needed resolution on mobility description.

The following diagram describes the chain going from human demand to energy consumption, for several energy-service systems. It is not a dynamic description of the transition but rather a picture of the demand-side of the energy system at a given time. However, in green (top line) are represented the levers triggering evolutions of this picture.

For the sake of illustration, the following energy-service systems have been described in the diagram:

- The (passenger) mobility system fulfills the needs of people to access a variety of activities, goods and services (Briand, Lefevre, & Cayla, 2017).
- The laundry washing system fulfills the needs of people to wear clean garments
- The space heating system fulfills the needs of people to feel warm
- The material goods production system participates in fulfilling the needs of people to have access to material goods

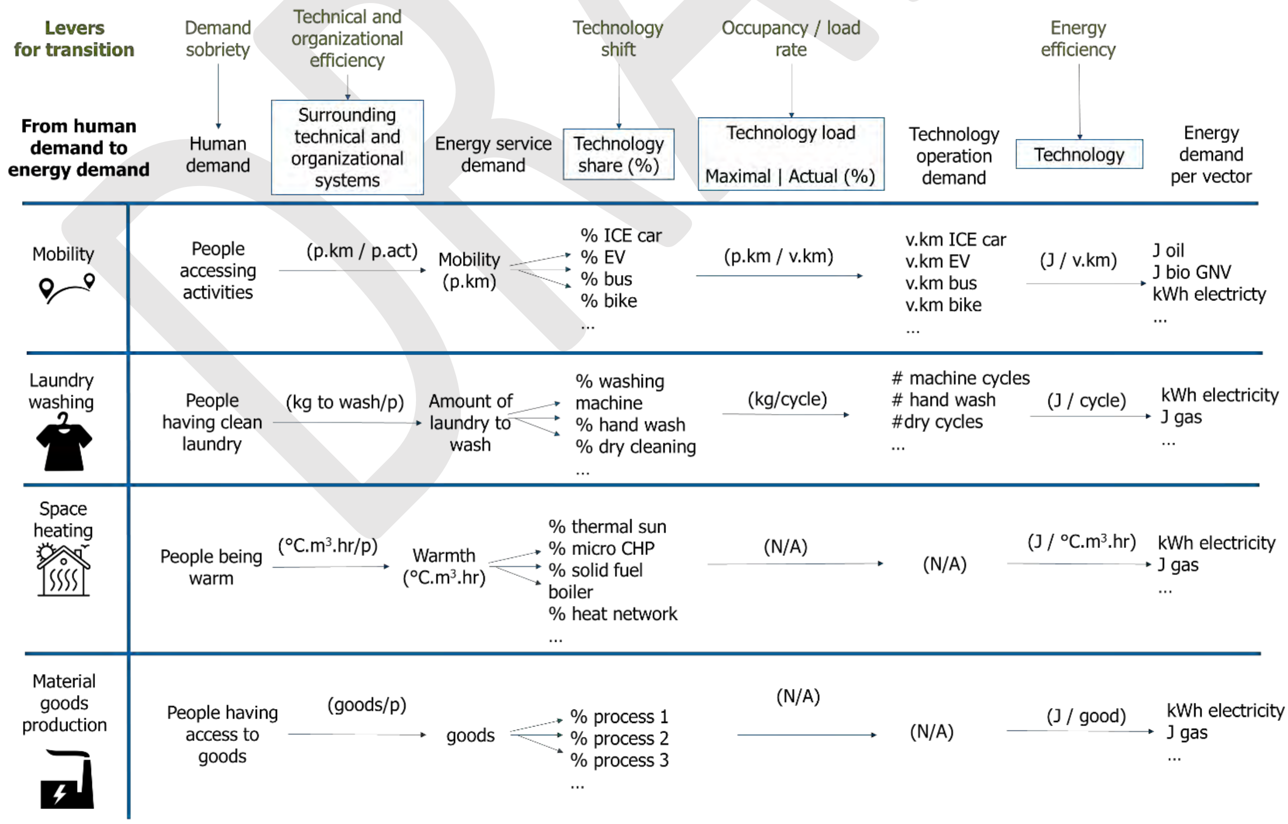

Figure 4: The energy consumption frame for a common behavior-based approach

There is not necessarily a bijection between a human need and a specific energy-service system fulfilling it. For example, the steel production system is linked to several human needs (all the applications of steel). The other way round, eating needs are associated with several energy-service systems (farming system, agricultural system, food transformation industry, freight…); "having access to goods" needs are also associated with several energy-service systems, such as the material goods production system, the freight system, and the (passenger) mobility system.

2. Central concepts of the framework: a chain from human demand to energy consumption per carrier

This diagram provides a useful frame to think energy demand and all the levers which can be activated to act on energy demand. By no means does it represent the causal chain of how energy consumption is determined in reality. Rather, it helps taking into account all the influencing factors of energy consumption. Here are the main concepts of the framework:

a. Human demand

There is certainly no proper way of measuring human demand, but it is conceptually a growing function of population: the more people, the more "people feeling clean" need, hence the more demand for people feeling clean. This concept is very close to what economists call "utility", or welfare. Utility is maximized for a person when the greatest possible share of its human demands are fulfilled (for a given income, for example).

Communication campaigns (advertisement) promoting consumption which does not exist yet (such as new entertainment devices, or, in past times, the invention and mass production of cars, or of phones), or the mere observation of others using new technologies, lead to create new, or increase, human demand.

b. Energy service demand

This term is coined by (Le Gallic, Assoumou, & Maïzi, 2017). It represents how much the energy service system must operate to fulfill human demand. In essence, an energy-service system transforms its environment; this transformation is what is called here the *energy service*. For example, the mobility system moves people from places to places. The laundry washing system makes dirty laundry clean. An entertainment system (for example composed of TV sets and computers) modifies the visual and sound environment of people for entertainment purpose. The space heating system makes ambient air warmer. And so on.

In Figure 4, examples are provided with specific units for energy service demand, such as p.km for mobility, or kg of laundry to wash. These units can be discussed to better represent the energy service. For example, laundry washing could also be measured as a volume, in m^3 of laundry to wash instead of a weight.

c. Technology operation demand

It represents how much the considered technology has to operate given how loaded it is. For example, how many kilometers must be run by ICE cars each year, or how many wash cycles must be performed by washing machines each year.

d. Energy demand per vector

Finally, energy demand represents the amount of energy which is required for each specific technology to operate under the previously described conditions. This amount is associated to specific energy vectors.

3. Levers triggering evolutions of the energy demand

In Figure 4, arrows do not represent a transition through time from the left to the right but rather "influence" links between different concepts within a static image of the energy demand-side, for different energy services. Here are some reading keys illustrating those influence links:

- The activation of the *demand sobriety* lever can be read as: *less* human demand is fulfilled. For example, people accessing less activities, people having less clean laundry, and so on.
- The activation of the *Technical and organizational efficiency* (TOE) can be read as: *same* human demand is fulfilled, *with a lower amount of* energy service demand. For example, people accessing the same activities with a lower amount of passengers.km; people keeping the same laundry cleanliness with a lower amount of laundry to wash; people filling as warm with a lower amount of heat transmitted to the air in living places, people having access to the same goods with less goods, and so on.
- The activation of the *technology shift* lever can be read as: energy-service demand is fulfilled *by a different* technology share.
- The activation of the *load rate* increase can be read as: For a given technology, the same energy service demand is fulfilled, with less technology operation demand. For example, the same amount of passengers.km by ICE car can be performed with less cars.km; the same amount of laundry can be cleaned by washing machines with less machine cycles, and so on.
- The activation of the *energy efficiency* lever can be read as: *the same amount of* technology operation demand can be performed *with less* energy demand. For example, the same amount of cars.km by ICE car can be performed with less oil; the same amount of washing machine cycles can be performed with less electricity; the same amount of heat transmitted to room air can be reached by thermal sun panel with less sun light; the same amount of goods produced by "process 1" can be performed with less energy; and so on.

The following sections describes the levers.

a. Human demand might be reduced through demand sobriety

The lever decreasing human demand (for a given population) is usually called sobriety. It is also sometimes referred as sufficiency (Roy et al., 2012; Samadi et al., 2017). We call it *demand sobriety* in order to differentiate it from technical and organizational efficiency, which is sometimes also referred as sobriety. It is the direct reduction in the human demand per capita ("utility" decrease), leading to energy consumption reduction all else being equal. For example, buying 1 TV set every 2 years instead of 1 per year for a household would be demand sobriety for TV set production. Using one's personal computer 3 hours/day instead of 4 hrs/day would be demand sobriety for access to entertainment.

Some authors argue that sobriety is not necessarily associated with unhappiness, even though it corresponds to a decrease in utility (less can still be enough (Samadi et al., 2017)). Notions of luxury and basic needs are relevant to think about demand sobriety: it may be considered as easy to reduce luxurious demand but unacceptable to reduce demand for basic needs (Demski, Thomas, Becker, Evensen, & Pidgeon, 2019; Roy et al., 2012). What "luxury" or "basic need" mean depends on each culture, economic context and era.

People may be willing to reduce their human demand for example under the influence of communication campaigns or education (Roy et al., 2012), on the long-term environmental or ethical impacts of their behaviors. It can also be activated through pull (reinforcement, carrot) or push (coercion, stick) measures (van Sluisveld, Martínez, Daioglou, & van Vuuren, 2016).

b. Surrounding technical and organizational systems (STOS) are a source of efficiency and of interactions within the energy service basket of consumers

The surrounding technical and organizational systems (STOS) are the set of systems surrounding the considered energy service system and having an influence on how much the energy service system needs to operate to fulfill the human demand.

For example, for the mobility system, people can have access to work through telework, which reduces the amount of trips people have to perform while fulfilling demand for accessing work; similarly, groceries can be delivered at home, etc. Also, city planning plays a role in the distances to travel to access activities through city density and functional diversity. The telework system, grocery delivery system, and city organization, are such surrounding systems.

For the laundry washing system, maybe clothes which need less washing can be produced, or cities can be less polluted, so that the same number of people feel they have clean laundry while washing less laundry. These would also be examples of surrounding technical and organizational systems.

For the space heating system, thermal insulation of buildings, design and orientation of the buildings, vegetation shading the building, city planning (taking into consideration dominant winds, vegetation effects, local climate…) etc are such surrounding systems. Design plays a role in heat naturally received from the environment (windows, shape etc) but also a role in how many inhabitants live in the same volume of building (Ko, 2013; Rickwood, Glazebrook, & Searle, 2008). Thermostat control through time enables to fulfill the same amount of thermal comfort while requiring less heat. Available warm and comfortable garments have the same role, and as such they are also part of the surrounding systems.

All these systems represent a source of efficiency levers (*technical and organizational efficiency, TOE*) enabling to fulfill the same human demand with a lower energy service demand, maybe at the expense of increasing the demand for another energy-based system; for example, telework system may require additional ICT equipment, additional buildings etc.

Energy services should be seen as a consumption basket (Roy et al., 2012) whose share evolves if TOE lever is activated, such as moving around less but using more ICT equipment.

These levers to modify the surrounding technical and organizational system are activated by the productive sector through technical innovation and new practices and/or by the public sector through investments in infrastructures or tax system evolutions (such as for city planning).

These systems are often long-lived and can lead to lock-in effects, such as energy inefficient houses' designs or energy inefficient urban forms (Roy et al., 2012).

Compared to the sobriety lever, TOE lever uses an artefact, or new way of organization, to reduce consumption while fulfilling the same human demand.

c. Technology share evolves through technology shifts

Technology share represents how much of the energy service (or transformation need) is performed by each different technology present in the system. It is based on a list of available technologies fulfilling the considered need in the scenario. A percentage of the total need can be allocated to each technology. Usually technologies use one energy vector, but some technologies might use several (e.g. hybrid rechargeable cars use electricity and oil).

For example, in the mobility system, different technologies of cars (fuel cell, Internal Combustion Engine (ICE), compressed gas…), buses, bikes (e-bikes, or traditional…) can be used to fulfill the mobility need. In the space heating system, different heating systems and types of buildings (especially categorized by thermal energy performance) fulfill the warmth need.

Levers modifying the technology share are provided by the productive sector through new technologies which may become part of the share (such as new personal mobility devices), new services and infrastructures around the existing technologies (such as charging stations for EVs, or bicycle repair shops for bikes); and accompanied by the public sector through investments in infrastructures (such as bicycles lanes) and through incitation (for example, subsidies for buying EVs). Communication campaigns by the private sector for one type of technology (advertisement campaign) or by the public sector can also modify the technology share.

In the mobility system, infrastructures lead to physically favor specific technologies. As they are long-lived, they can lead to lock-in effects (such as a road system designed for car use).

d. Technology load may be increased to make a given technology more energy efficient

Some technologies might be used differently so as to perform the same service while being used less (or more service while being used by the same amount). This is described by the occupancy, or load rate. This rates describes how loaded the technology is when it operates. The more loaded (up to the maximal efficiency load), the more efficient the technology when it operates. For example, washing machines, dishwashers, clothes dryers, vehicles, can be more or less loaded. In a similar fashion, lighting can be turned off when nobody is in the room, which enable to perform the same service by using the bulb less. This use characteristic does not apply for technologies which can only be used in one fashion (such as hair dryers, irons…) though. Modifying load rate requires modification of consumer's behaviors or of industry behavior (e.g in the freight sector), possibly through public incitation or communication campaigns.

In this framework, concerning heating system, heating more people with the same use of heating technology because more people live in the same place represents technical organizational efficiency.

e. Energy efficiency may be improved by technology improvement or by technology use optimization

Each technology used has a specific energy efficiency[6]. Energy efficiency is the lever associated with the technology. Energy efficiency can be associated to the design of the technology, or to the way it is used. Some technologies have energy optimal operating points and use cases. For example, ICE cars have an energy optimal speed, and an energy optimal way to be driven. For many technologies though, operation is automatically energy optimized.

Energy efficiency improvements from design evolution are uncertain. They are often explained in scenarios through global mechanisms such as the learning effect, with no concrete explanation for each technology of why the improvements should go on in the future on the same trend as before (see boundary conditions section).

Some technologies might be associated to several energy vectors, which may require to define several energy efficiencies.

f. Disagregation levels to get deeper in behaviors details

This framework provides questions to detect levers to reduce energy consumption; it also provides a way to think about the key explanatory factors of energy consumption from lifestyles, technical and organizational environment (infrastructures, available technologies…).

However, it handles only the average situation, which might not be sufficient for a detailed sociological account of how the demand evolves. To overcome this limitation, the framework can further be broken down into energy service sub-systems when it is deemed relevant with regard to different practices among sub-populations. For example, the mobility system can be broken down into three sub-systems depicting significantly different mobility practices: "Mobility in urban areas" / "Mobility in rural areas" / "Mobility in intermediate density areas".

A more sociologically detailed representation is proposed in (Le Gallic et al., 2017): they model the population and lifestyle system. Hypotheses can then be taken for specific groups of people which are homogenous in terms of energy service demand. For example, short distance mobility evolution can be proposed for households aged between 30 and 35 with 2 children living in rural areas for their daily commute trips. The model then computes the associated new energy service demand (in this example, the total number of travelled kilometers for passengers for short distance mobility).

The proposed model encourages scenario producers to be consistent between the new transversal lifestyles they imagine, their diffusion in the population, the demographic structure of the population, and the level of service demand.

For example, it may be difficult to imagine the overall, average effect of implementing a bike system in a country. Systematically imagining what different groups of individuals would do with such a system enables to make the sociological storyline much more precise and to provide an substantiated hypothesis for travelled kilometers for different modes with a bike system (The Shift Project, 2017).

g. Sobriety of efficiency? Often a subjective matter

Often, levers excluding demand sobriety are collectively called "efficiency measures", except for some TOE measures. Indeed, as TOE measures modify the energy services basket, some might consider that the overall

[6] Efficiency of an aggregate of technologies may be defined as the energy efficiency averaged over the whole set of the considered technology and the many ways they can be used). For example, small ICE car consumption may be averaged over the type of roads and driver profiles.

comfort of life is reduced. For example, it may be considered that wearing a sweater to reduce thermostat set point is an overall loss of comfort/utility. Similarly, it may be considered that reducing floor space par inhabitant by sharing more space represents an overall loss of comfort, and hence it would be called sobriety (such as in (Association négaWatt, 2014)). In other words, the use of the terms "sobriety" and "efficiency" in literature are often linked to a (necessarily subjective) judgement of loss of comfort. Sobriety is associated with an overall loss of comfort whereas efficiency is associated with no loss of comfort (Brown et al., 2018).

h. Different actors can trigger different levers

As illustrated in the examples hereabove, it is not only individuals who have to be targeted for energy consumption policies. Lifestyles with certain levels of comfort and high energy services demand have not necessarily evolved from individual choices. For example, industrial offer for cars scarcely provide small and low power vehicles. Infrastructure design might make low-energy mobility modes dangerous, etc (Roy et al., 2012). Hence the different levers affecting energy demand involve political, cultural, physical environment and individual aspects. Such levers rise important questions about loss-of-comfort sharing among society (see desirability section).

Recommendations for scenario producers

For scenarios determining demand evolution through a behavior-based approach, the described framework should be used for adopting a common language about demand evolution. A list of the different energy service systems may be provided; e.g. long-distance mobility (system), space heating (system), and so on. For each of them, a list of the different sociological aspects which are taken into account may be provided; e.g. fabric of living place: urban or rural; level of revenue; type of building, and so on.

For each energy service system, the types of levers which are activated may be described. If levers other than energy efficiency are activated, substantiation might be provided about the desirability of the lever. In order to do so, the possible losses of comfort should be qualitatively assessed for each lever, as well as its possible side-benefits. Considerations on time horizon may be included in this assessment. For example, carpooling may generate a loss of comfort on the short-run for schedule reorganization, but generate social link on the medium-term.

D. Rebound effect: a complex economic effect heterogeneously integrated in future studies

Now that the proposed frame to think energy demand has been described, we use it to discuss rebound effect and how it is integrated in the computation of energy demand in different future studies.

1. Rebound effect on energy demand is a complex economic effect corresponding to a greater energy demand than what would have been expected after some energy saving actions

Rebound effect is the reduction in expected gains from a policy, market and/or technology interventions aimed at environmental efficiency improvements, because of behavioral or other systemic responses.

Typical examples of rebound effect are an increase in car use when fuel efficiency is increased, or the purchase of a journey by plane thanks to money from energy savings at home.

It is generally expressed as a ratio:

$$RE = \frac{Expected\ savings - Actual\ savings}{Expected\ savings}$$

For instance, if a 5% improvement in vehicle fuel efficiency results in only a 2% drop in fuel use, there is a 60% rebound effect. Rebound effect can be higher than 100%. This is called 'backfire'.

Rebound effect theory can apply to the use of energy consumption but also on any natural resource or other input, such as labor. It usually happens after a change in costs, but can more generally be related to other types of changes like time savings, change in weight, available space, etc. Despite these are interesting elements to keep in mind, we focus here on rebound effect on energy consumption happening through change in costs.

It is a key phenomenon with broad spectrum and significant impact: it should be addressed for every measure related to energy efficiency (thermal building renovation, vehicle fuel efficiency, etc.) or additional purchasing power (through additional growth, energy prices reduction, sobriety, etc.). However it is also challenging to quantify.

As explained in note about Rebound effect, three types of rebounds regarding energy services are usually depicted in the literature:

- Direct rebound is an increase in demand for the now cheaper energy services. For example a reduction in heating costs after energy efficiency measures is followed by an increase in chosen household temperature.
- Indirect rebound is an increase in demand for other energy services after the initial cost reduction in some goods or services. For example the same reduction in heating costs after energy efficiency measures can also be followed by the purchase of a bigger and more polluting car thanks to money savings. Indirect rebound tends to be less studied than direct rebound effect but should not be neglected. In some cases it has a bigger impact than direct effect.
  Both direct and indirect rebounds are demand-side behavioral responses, and thus microeconomic effects. They are also both composed of a substitution and an income effect.
- Economy-wide rebound is an increase in energy use after an energy efficiency improvement through market adjustments and innovation channels. It is thus a macroeconomic effect. For example the reductions in energy and carbon intensities lead to a reduction in producer's costs and, therefore, prices and consequently more output and exports (Barker, Dagoumas, & Rubin, 2009). It is far less understood than microeconomic rebounds. Economy-wide effect is composed of macroeconomic price and growth effects.
  Evaluating economy-wide rebounds brings the same challenges as in most macroeconomics research: global economy is a single, interconnected, complex dynamic system, making definitive arguments about cause and effect probably impossible.

These rebounds in consumption can be described as emerging from different mechanisms:

- Income mechanism[7] is related to extra-money. By making energy services cheaper, energy efficiency improvements increase the real income of households. The question here is: "If a consumer is given an extra euro, how is it going to be used?" The consumer can thereby increase consumption of the improved service (direct rebound) or spend it on another good or service (indirect rebound). This is determined by consumption structure (ADEME, 2016).
- Substitution mechanism is related to a change in relative prices. After an energy efficiency measure, the improved service is now cheaper than before. Therefore, with the same real income, households may shift their consumption patterns according to the new relative prices between goods and services. This mechanism can both lead to an increase and decrease in energy consumption and/or GHG emissions depending on the substitution choices that are being made.
- Macroeconomic price mechanism applies through the equilibrium price of energy: after an energy efficiency improvement the energy demand is reduced. This drives down the price, which encourages a re-increase of demand.
- Macroeconomic growth mechanisms arise from innovation and reduction in energy costs for producers (particularly for energy-intensive industries), especially through three main channel:
  - Deployment of inframarginal resources, which is money in the economy that would previously have been spent on energy. It can be seen as a supply-side analogy to the income effect.

[7] The different mechanisms are usually called "effects" in the literature. However the word effect is usually used to describe an impact *on* something, whereas we want to describe here a process *by which* rebound effects appear, hence the use of the word "mechanism".

- o Sectoral reallocation. It can be seen as a supply-side analogy to the substitution effect and is most commonly discussed: if an industry acquires a more energy efficient process, it then spends more in using this extra process.
- o Induced innovation in one sector that may spill over to others. For example, the development of lighter, stronger materials for fuel-efficient cars might lead to better airplanes, boosting energy use in the aviation sector (Gillingham, Kotchen, Rapson, & Wagner, 2013).

Note that those rebounds and mechanisms may be described under different terms in the literature, or may contain slightly different meanings. These descriptions always relate to the economic theoretical frame which is used. As explained in the note about rebound effects, measurements of the different rebounds in developed countries economies lead to a low estimate of 20 % for the aggregate rebound effect after energy efficiency measures.

Rebound effects are complex effects involving the whole economy. In the meantime, they are known to happen in specific cases which extensively happen in future studies' scenarios such as energy efficiency improvements. Sobriety measures may be considered to trigger the same kind of effects as energy efficiency measures (e.g., income mechanism and macroeconomic price mechanism would happen under such measures).

2. Rebound effect is heterogeneously integrated in different studies

a. Technical studies do not implement any economic feedback between the energy system and energy service demand whereas this feedback is the essence of rebound effects

Future studies using the behavior-based approach to simulate energy demand implicitly cover the rebound effect by entirely defining the energy consumption behaviors of individuals and companies. The studies we reviewed in this category do not explicitly consider rebound effect: lifestyles and behaviors are described as if rebound effects were already accounted for but no narrative is provided to explain how this happens.

Conceptually, this aspect could be handled in two ways for behavior-based approaches:

- either rebound effects are prevented by some political measures in scenarios. The goal of these political measures would be to contain, or reduce rebound effects. For example, measures diverting purchasing power to lower energy consumption activities, or to lower CO_2 emissions activities. Note that to be efficient these measures must take into account macroeconomic effects. For example, taxation on energy for all economic actors could be an efficient way to divert consumption from high energy activities, but the fact that taxation income for the State will be redistributed in some way should be taken into account.

- or they are already included in the described behaviors. The second way would consist in providing rebound effect simulation results, or a narrative, to justify the fact that consumption behaviors could be re-organized in the proposed way without requiring any policy to contain rebound effects.

In a very similar fashion, some studies using GDP-based approach for demand define demand in their transformational scenarios by applying some energy efficiency measures to their reference scenario (such as in (ECF, 2010; Greenpeace, 2015)). However, the results of these energy efficiency measures do not consider any rebound effect. The measures are just applied, and the resulting demand becomes an input to determine the supply-side of the energy system.

Similarly, studies using the supply-side only approaches merely assume an energy demand level with no regard to rebound effects.

Finally, the German study (Fraunhofer ISE, 2015) cost-optimizes the energy system supply-side along some parts of the demand-side. Technology operation demand is a boundary condition for this study (whereas in the supply-side only approaches energy demand is the boundary condition). The optimization algorithm then selects the specific demand-side technologies fulfilling this demand, considering their costs and the energy savings they enable. No direct rebound effect is considered in the hypotheses of these energy savings.

All these studies have a common point: their demand levels are economically independent from the energy system evolution. In other word, there is no economic feedback loop between energy demand and energy system evolution.

Hence by nature those studies cannot model any form of macroeconomic rebound effect. We call those studies the *technical studies* (as opposed to the *partial equilibrium studies* in which the demand is influenced by the energy system evolution with feedback loops).

b. Partial equilibrium studies implement this feedback to some extent; however this does not necessarily imply they model rebound effects

Partial equilibrium studies use models implementing a feedback loop between the energy system evolution and the demand evolution. As a consequence, they have the potential to simulate some forms of macroeconomic rebound effects.

We found two main types of models in this category. PRIMES represents the first type and POLES and the WEM represent the second type.

PRIMES computes energy demand through representative consumers (a consumer for households and a consumer for industries); each representative consumer is actually a distribution of consumption behaviors (for example, modeling different mobility behaviors, distributed over different modes). The representative consumers have a global budget to spend, directly determined by the exogenous GDP hypothesis. They allocate this budget on different activities, some of them triggering an energy service demand (driving one's car, turning on the oven, producing goods (for industries)…), the others not (for example, buying a table, food or an oven) (see Figure 5). Hence if the budget increases, or if energy efficiency increases, or if energy price decreases, the representative consumer spends its extra purchasing power in extra consumption.

For example, if representative consumers acquire energy efficient appliances (for example, a more energy efficient car), then their energy consumption decreases, and their extra purchasing power is reinjected in other consumptions, as defined by the utility function (that is, the modelled preferences of the consumers). Note that if the extra purchasing power is reinjected in more of the same energy service consumption (more driving), it is called direct rebound effect. If it is reinjected in other energy services (such as heating more their house), it is called indirect rebound effect.

If the extra purchasing power comes from an energy price decrease (e.g. because the supply-side system becomes less expensive), then the simulated rebound effects are macroeconomic price effects.

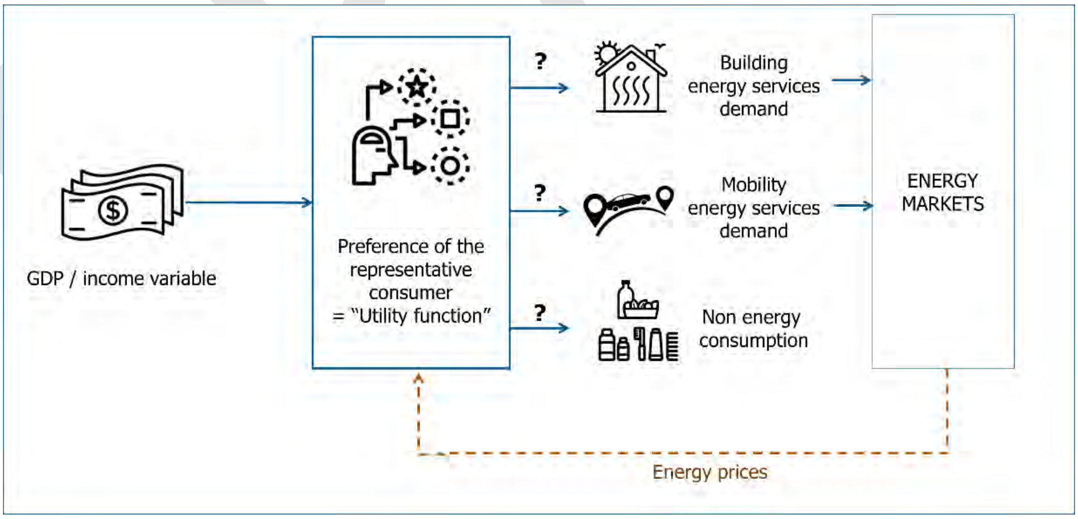

Figure 5: PRIMES model simulates representative consumers which allocate an exogenously fixed income to different consumption activities. Hence if the budget increases, or if energy efficiency increases, or if energy price decreases, the representative consumer spends its extra purchasing power in extra consumption. This models direct, indirect and macroeconomic price rebound effects, as long as some growth rebound effects.

Hence PRIMES models several types of rebound effects (direct rebounds, some indirect rebounds and price rebounds). However, PRIMES cannot model all the rebound effects because it only models the energy sector. Hence, for example, extra purchasing power leading to buying more goods does not loop back to the goods production sector.

POLES and the WEM operate in a different way to determine energy demand evolution. They first compute the energy service demand from GDP and other macroeconomic variables of the different regions they model. From the energy service demand, they define which technologies will fulfill the demand based on different exogenous variables as well as on endogenously computed energy prices. These technologies then lead to energy carrier supply-side evolutions, and to new energy prices.

The nature of the feedback loop from the energy system to the energy demand is one of demand elasticity to price for technology choices. This way to operate only partially models rebound effects. No purchasing power is modelled hence energy efficiency directly leads to a lower energy consumption without direct or indirect rebound effect.

However, for some consumption sectors, extra feedback loops are implemented directly towards the energy service demand: energy service demand depends on energy prices. This enables to take into account macroeconomic price rebound effects (at least partially).

The most advanced account of rebound effect in these models is the transport sector of the WEM: a specific elasticity coefficient for overall transport demand is included based on the unitary consumption of vehicles. This feedback loop is specifically dedicated to modelling the direct rebound effect in this sector.

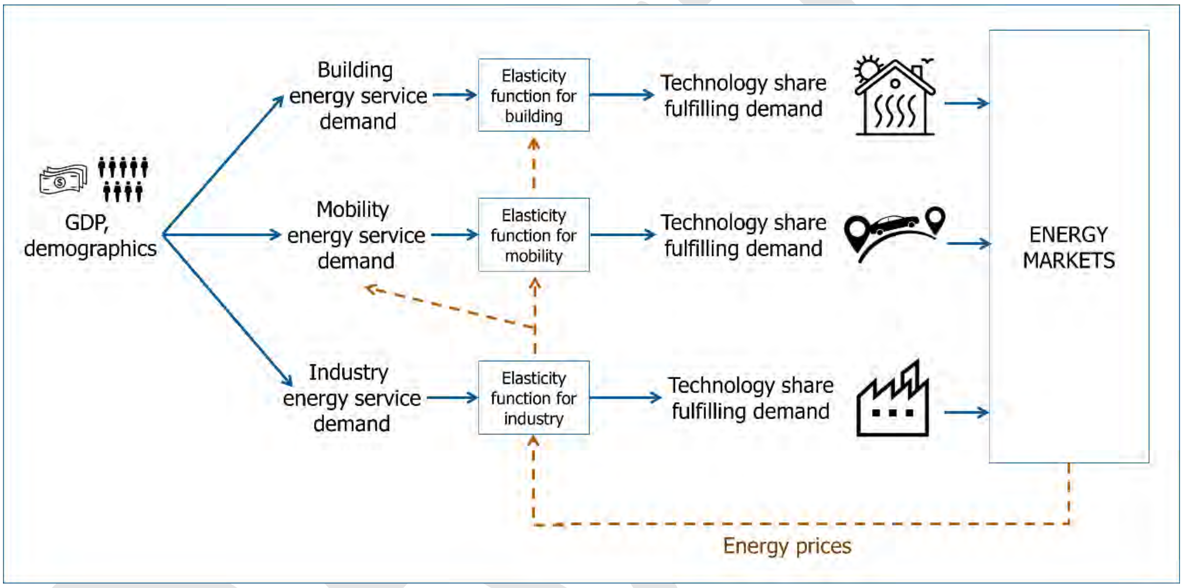

Figure 6: POLES model does not implement specific mechanisms to model rebound effects. However, its structure enables a partial account of price rebound effects, especially in the mobility sector through an elasticity feedback loop between energy price and mobility service demand.

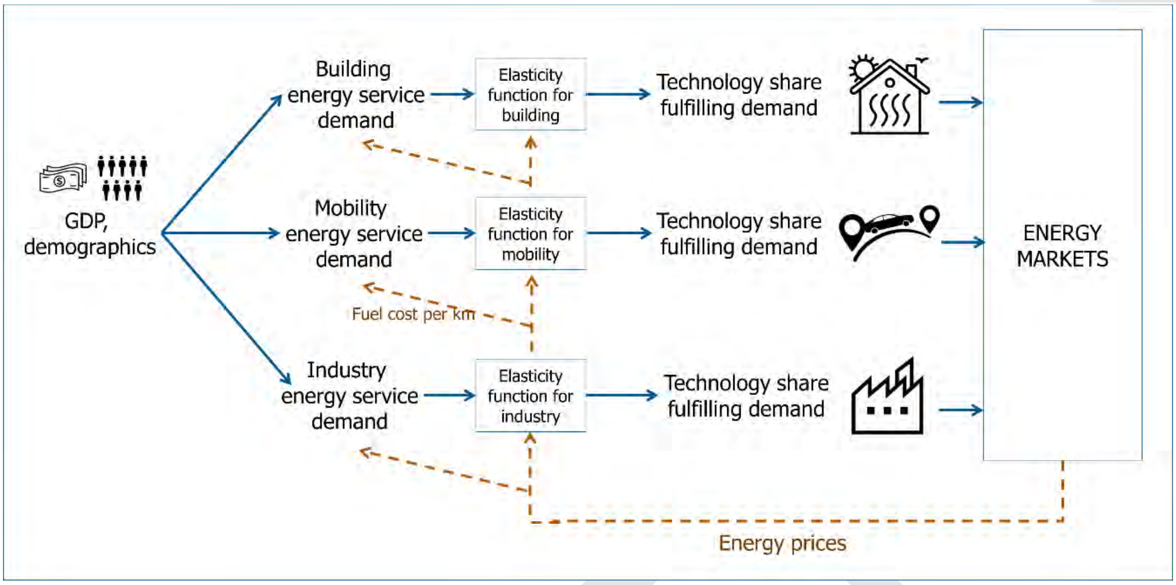

Figure 7: The WEM implements a specific mechanism to model a direct rebound effect in the mobility sector. In other sectors, no specific mechanisms are implemented but price rebound effects may be partially simulated through elasticities between energy prices and energy services demand.

Hence these models implement some form of price rebound effects, and partially some direct rebound effects.

Note that the simulations of some rebounds in PRIMES, the WEM or POLES depend on the specific parameters defining their magnitudes (such as the utility function in PRIMES, and the different elasticity functions in POLES and the WEM). These parameters are tuned based on measurements of the real world, hence they depend on the economic frame and economic policies that have been implemented in the real world so far. These values might not adequately model what would happen under policies different in nature or in magnitude than what happened in the past. In other words, this tuning may not be adapted to simulate transformational scenarios[8].

Recommendations for scenario producers

Scenario producers should be explicit about the interaction between energy service demand evolution and the energy system evolution in their study: *is the study a technical one or a partial equilibrium one?*

Scenario producers designing *technical studies* should consider and report the following aspects of rebound effect:

- behavior and technology evolutions, or economic evolutions prone to generate rebound effects such as behavior changes driven by sobriety, or more energy efficient technologies, or large investments in the transition industry
- policies required to obtain the described overall behaviors, such as policies limiting the rebound effects. By doing so, macroeconomic considerations may be required.
- other reasons to justify the fact that the described overall behaviors would not be prone to rebound effects (such as already manually integrated rebound rate).

Scenario producers designing *partial equilibrium studies* should consider and report the following aspects of rebound effect:

- transition actions which are prone to generate rebound effects, such as energy efficiency measures or large investments in the transition industry
- the different types of rebound effects which are modelled

[8] In PRIMES, preferences of the representative consumer seem to be fixed for the whole scenario timeframe, as suggested in (European Commission, 2011).

- the parameters at the origin of the modelled rebounds (elasticities, utility function…), and if they are static along the scenario timeframe. If they are dynamic, considerations on their determinants may be provided.

In case some rebound effects are not modelled, a narrative substantiating the fact that the absence of modelling does not impair the scenario internal consistency (policies dedicated to avoid these rebound effects, demonstration that these effects have negligible impacts…) should be performed.

Some more details on typical values for rebound effects can be found in fiche rebound effect.

E. Energy efficiency is the king of levers in the scenario community, leading to an overall focus on technologies

1. Levers other than pure energy efficiency modifies the comfort of use

Energy efficiency is generally seen as the best and top priority lever. Indeed, it enables to reduce energy consumption without changing habits at all.

Demand sobriety requires significant behavioral changes (also see section on lifestyles); all other levers do not reduce human demand, in theory. In practice, losses of comfort or side benefits may appear:

- TOE enables to fulfill human demand with a lower energy service demand; however, it might come with an overall reduction in comfort, or utility, depending on the cases. For example, putting two sweaters on may feel less comfortable than having a T-shirt (T-O sobriety for heating system). Teleworking comes with side effects (for example, not seeing team members so often) which may be felt as uncomfortable, or may not be accepted by companies (loss in productivity). Flat sharing enables to lower heating space service demand, but may be seen as uncomfortable.
- Technology shift towards lower consumption technologies may also be associated with some sort of incomfort. For example, switching from ICE car to electric car is associated with a shorter range, and longer charging times, which may be felt as less flexible and practical. Switching to bike for shorter trips may be associated with lower comfort especially during rainy, or hot weather; it is however associated with health positive effects. Switching from gas house heating system to a heat pump may be associated to a lower comfort during very cold period (heat pump less efficient).
- Load rate increase to decrease energy consumption may also be associated to a lower level of comfort. For example, long-distance carpooling is an uncomfortable practice for some, and it may be inconvenient to adapt schedules for short distance trips; for others, carpooling may be a source of positive social link.

As a consequence, all the levers but energy efficiency may lead to acceptance issues, as they can impact lifestyles. On the contrary, energy efficiency measures are not associated with any inconvenience. Hence it represents a central lever for policy to target (Riahi et al., 2012).

It comes as natural that most scenarios gives energy efficiency measures the greatest role in energy consumption reduction. On the contrary, few scenarios see demand sobriety, T/O sobriety, technology shift or load rate increase as levers.

2. The scenario community mostly focuses on technological improvement through energy efficiency, risking to neglect the insights from social sciences

In virtually all scenarios, energy efficiency through technological improvement is the preferred way of action because it is easily translated into market-based levers (which easily fit market-based models) or into technology-levers (which easily fit optimization models), and because it apparently goes towards all sustainability goals with putting all the transition effort on corporations, asked to propose more energy efficient designs at lower costs, and ideally lower social and environmental negative impacts; in turn, no change at all in lifestyles or in society organization are required, which avoids to rise more difficult questions such as geopolitical, political, institutional and cultural questions (also see lifestyles). In other words, energy efficiency provides a substantial comfort for scenario producers: even their transformational scenarios remain in a roughly *business-as-usual* world, except for the availability of technologies part. This considerably limits the amount of extra-hypotheses necessary to describe the world and also limits the possibilities of critiques from stakeholders, as a low number of transformations is proposed. In turn, questions and critiques naturally focus on the technological feasibility of such improvements (in terms of dynamics with regards to the transition deadlines) as well as on their various impacts on environment, society and economy.

Through this massive use of energy efficiency in scenarios, the debate on energy transition naturally focuses on technologies, their costs and impacts instead of keeping a global outlook including a larger amount of insight from social sciences (psychology, sociology, political sciences…). Technological improvement, in those scenarios, is actually a necessary condition for not adapting behaviors and institutions. Hence technological improvement is a key parameter of those scenarios and as such should be thoroughly substantiated.

Only local/national scenarios which are resources-driven propose other ways of action. Indeed, they adapt behaviors and practices to local resources, as mentioned in the introduction.

3. In scenarios, energy efficiency evolution is determined through a technology-rich approach or directly assumed

As previously explained, scenarios using a GDP-approach to determine demand start from GDP and then determine demand per sector in line with the GDP evolutions.

Most of them assume global energy intensity of the GDP evolutions per sector in an aggregated way. Hence they make no study about individual technologies and instead make macro assumptions about technology improvements (DGEC/CGDD/ADEME, 2015; ECF, 2010; Riahi et al., 2012). The assumed energy intensity trends are usually in discontinuity from historical trends, as illustrated for the developing countries' trend in (Riahi et al., 2012), going from -1.0% per annum in the past to a sustained -3.1% per annum until 2050 in the Efficiency pathway.

Even though PRIMES has a GDP-based approach, it is also *demand-side technology-rich*. In other words, it defines precisely different technologies in a disaggregated way, and the evolution of the stock of these technologies through models of the stock and the associated flows (technology being bought and being discarded).

Hence studies using PRIMES model define several vintages ("base", "improved", "advanced" and "best technology") for demand side technologies. These vintages have increasing capital costs and efficiency (the more advanced technologies are more expensive but more energy efficient). PRIMES assumes a trend to buy best technologies as market barriers are removed and as carbon price increases. Hence a link is created between energy efficiency policies and technologies demand and production. In other words, technologies share evolves through market-based mechanisms (European Commission, 2016). Energy efficiency improvement emerge from the best technologies being integrated to the technology mix through market mechanisms.

Studies using the behavior-based approach to determine demand, define a storyline for the evolution of demand including evolution of technologies and their uses. They are also demand-side technology-rich, but the use of the technologies is largely driven by energy consumption behaviors and by the benevolent planner defining the technology share. In those scenarios, the technology choices of the benevolent planner are substantiated through a storyline (ADEME, 2012; Association négaWatt, 2014; RTE, 2017; SLC, 2017; Barton et al., 2013).

4. Providing a *concretely* substantiated storyline for energy efficiency improvements is key

Technology-rich scenarios can easily provide a storyline about how and why technologies evolve as they do, unlike technology-poor scenarios (those assuming a global energy efficiency evolution). However, as a key hypothesis, energy efficiency improvement should be concretely substantiated (see Future studies).

(Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012) suggests several ways to foster energy efficiency: increase energy price, measure energy consumption at household level to provide an incentive to reduce consumption through a proper price signal, provide more information about appliance energy consumption at selling point, raise awareness among industry professionals about energy consumption of the appliances they produce.

On the one hand, mitigation scenarios assume a large leap between the currently observed energy efficiency gains and the ones happening all along their timeframe, asking the question of the feasibility of such a sustained leap (Samadi et al., 2017). On the other hand, it may be argued that no strong effort has been made in that direction because incentive is for most products to reduce production costs (mostly accounted by work force) as opposed to reduce energy consumption[9].

Recommendations for scenario producers

Scenario producers using the GDP-based approach should provide an assessment of the technological demand-side effort which is performed in their scenarios in terms of energy efficiency, via the evolution with time of the relative decrease in GDP energy intensity compared to previous year.

All scenario producers should provide a storyline to thoroughly substantiate how this energy efficiency effort will be sustained in their scenarios, especially for scenarios putting emphasis on energy efficiency, along the following aspects:

- Sustained technological improvement: under what incentive will companies decrease energy consumption of their products? Where is the room for technological improvement as seen from today, for each technology (including business-to-business (B2B) technologies)?
- Sustained incentive to buy energy efficient technologies: under what incentives will consumers (individuals, companies, and states) buy energy efficient products? In particular, in which domain(s) and under what incentives will companies switch to energy efficient processes?

F. Zoom on the practices for determining demand evolution in different consumption sectors

The proposed framework can be used to summarize the future studies practices when it comes to determine demand evolution under a behavior-based approach. We propose such a benchmark of observed practices for the usual different consumption sectors: building, passenger mobility, freight and industry/agriculture.

1. Building sector

Building demand is usually composed of space heating, water heating, and electric appliances. Demand for space heating has a large inertia since it is linked to building envelope. Other aspects of building demand (water heating, cooking, electric appliances) have a lower inertia (Association négaWatt, 2014).

Demand in the building sector can be segregated by the functions of buildings: housings or commercial, tertiary or industry buildings and by the types of buildings: individual house or shared buildings.

a. Space and water heating and cooling

Space heating/cooling directly depends on level of temperature demand (human demand), building surface and building thermal performance (technical and organizational system). Hence for space and water heating/cooling, building stock can be usefully separated into existing buildings and new buildings.

Existing buildings are those existing at start year of the scenario. Their number decreases with time, with the demolition rate. They can be retrofitted for thermal insulation. Scenarios usually specify the type of retrofit which is performed (what parts of the envelope are insulated, double glazing, etc) (Barton et al., 2013). Within the existing buildings, further distinction can be usefully made per thermal insulation performance and per type of space

[9] Only for a few products/services does energy consumption represent a significant cost. For example, commercial aviation sector has a strong incentive to reduce kerosene consumption because kerosene represents the greatest part of the price for final consumer.

heating/cooling system. Thermal insulation performance can be evaluated through the age of the building (Association négaWatt, 2014). Similarly, water tanks for hot water can be insulated.

For new buildings, growth has to be estimated: population growth as well as hypotheses about surfaces per inhabitant. These buildings are generally not retrofitted as they are built with insulation standards and heating systems standards. This is why they can be separated from existing buildings. The energy efficiency standards for new buildings may evolve during the scenario timeframe.

Dwelling size significantly depends on the type of dwelling: individual houses or shared buildings.

For tertiary and commerce buildings, the volume of buildings can be associated with demographics, amount of service per inhabitant, and surface per unit of service. Services address different audiences. Hence the level of each particular service can be indexed on the evolution of its target population. For example, education targets people under 25 and as such demand for education can be projected using demographic assumptions for this share of population (Association négaWatt, 2014).

Determining air cooling consumption is more difficult for temperate countries because population is not yet equipped in cooling systems and the emerging need from climate change is difficult to assess (Association négaWatt, 2014). (Schweizer & Morgan, 2016) perform an assessment for the US based on a regression of equipment rate versus ambient temperature for different States.

Energy demand from space heating then has to be translated into vector demand, through the *technology share*. District heating, community scale biogas CHP, fuel cell micro CHP, stirling engine micro CHP, solid fuel boiler, oil fired boiler, resistive heating, ground-source heat pump, gas boiler… (Barton et al., 2013)

Each technology is associated with a vector and an energy efficiency. Hypotheses on energy efficiency evolution can be made for each technology.

The same has to be made for water heating. Technology choice can be made depending on the type of building: individual house or shared building (Association négaWatt, 2014).

b. Domestic appliances

Domestic appliances cover equipment for lighting, cooking (cooking robots), cooling (fridge-freezers, refrigerator and freezers), wet appliances (washing machines, dryers and dishwashers), and brown appliances (TV, video/ DVD players, set top boxes, ICT, telephone chargers, etc), as well as fans, pumps for ambiance conditioning, vacuum cleaner, iron, hygiene appliances (hair dryer, hair), DIY appliances, elevators…

These appliances are very generally thought of as fueled by power, as opposed to other energy vectors. Hence demand analysis is a bit simpler than for other types of demands: all the technologies are associated with electricity. However, still several technologies with different energy efficiencies and costs can be modelled, and the evolution of the appliance mix can be modelled.

Demand from electric appliances can be estimated based on a highly disaggregated method, by analyzing each use: within what context the appliance is used, how these uses can evolve, what the efficiency of the used equipment is. Hence several types of human demand are defined, such as laundry washing, laundry drying, ironing, dish washing, cooling food, freezing food, lighting, TV entertainment, sound entertainment, communication, air circulation, elevators and so on (Association négaWatt, 2014). Also, for conservative rationale, new, unknown uses can be added (Association négaWatt, 2014).

The primary driver which is used in scenarios to determine demand is households' number growth, based on demographics hypotheses.

Then some scenarios implement demand sobriety: reduced demand for TV entertainment, stabilization of the size of TV sets, enabling a stabilization of their consumption (Association négaWatt, 2014).

Scenarios propose the following TOE levers:

* evolution of the number of appliances per household (greater household density favors communalization of equipment use such as lighting, fridges, cooking, fans) (Association négaWatt, 2014; Barton et al., 2013).
* Evolution of electronics so that appliance sleep mode consumes less power.

They propose load rates evolutions for washing machines and dryers as well as for fridges and freezers, based on an analysis of current practices. These evolutions are slow because they happen through an adaptation of the appliance size to household demand (Association négaWatt, 2014).

Finally, some hypotheses about energy efficiency of appliances are made.

The same kind of method can be applied for tertiary specific electricy uses. These can be gathered into the following categories: lighting, informatics, tertiary processes (medical imagery), building management (elevators…). It also includes such services as public light, telecommunication operation, food storage, water management. Finally, some research facilities, as well as the military sector could also be considered for demand analysis.

2. Mobility sector

a. Different types of mobility demands

Mobility system is a complex system, aggregating several different natures of human demands. Hence in the behavior-based approach, mobility demand is divided in several categories in order to estimate its evolution in a realistic way.

Human demand can be categorized along the following dimensions (Association négaWatt, 2014).

* Type of trip (based on its distance, frequency and motive)
* Urban density of the trip
* Distance of the trip

Other categorizations have been proposed (The Shift Project, 2018):

* Urban density of the trip
* Distance of the trip
* Popularity of the trip (possibility to communalize the trip with other people)
* Specific need to transport a load or person

These categories are important because they are drivers of TOE, occupancy rates and technology share[10]. For example, the urban density of the trip determines which mode can be used and hence influences the technology share. (Le Gallic et al., 2017) determine those important categories by decision tree analyses based on large mobility surveys.

b. The levers to curve energy demand in mobility

A few scenarios implement sobriety through a reduction in long-distance trip average distance, long distance trips being considered in this case as a luxury which can be partly questioned.

Usual TOE levers are telework, grocery delivery and city planning, each enabling to reduce the average distance of trips for different motives while still providing access to the motive.

These levers are triggered by energy prices increase, flight taxes, regulations on access to city center by car, investments in infrastructure and so on.

Within passenger mobility, technology shift is usually from ICE cars to electric cars, and/or from privately owned car use to other means (public transportation, bike, shared small vehicles). The shift may be triggered by space densification hence shorter distances to travel; public transportation development for urban areas and specialized taxis for rural areas; car sharing systems; bike system development; or natural cultural trends from the youth.

[10] Usually called modal share for mobility

Load rate (usually called occupancy rate for mobility sector) may be increased for car use through carpooling policies (infrastructure implementation, infrastructure allocation).

Scenarios also assume energy efficiency improvements for the different types of vehicles.

Energy efficiency, as measured in consumed energy per km travelled, depends on the use of the vehicle, such as heating and cooling of the vehicle, the way to drive (especially speed and acceleration patterns), the quality of the road and outside temperature for ICE vehicles (colder weather means a lower engine efficiency).

For ICE cars, heating the car requires no extra consumption because heating comes from the heat losses from fuel combustion. However, cooling the car leads to extra consumption, between 3 and 20 % (« Heating and Car Mileage », 2009).

For EVs, engine operation and efficiency does not depend on temperature. However, car heating (and cooling) comes from extra power consumption, which represents a 10 to 20% extra consumption compared to no car heating or cooling (« Heating and air conditioning in cars », 2019). Hence climate and weather dependence is greater with EVs than with ICE vehicles.

3. Freight sector

Freight system induces an energy demand. Freight could be seen as the system enabling the connection between end-consumers and products. As such, last mile delivery could be included in freight system even if it is performed by the end consumer herself, which is the view we adopt here.

For freight demand, no scenario invokes demand sobriety (which would be equivalent to deciding not to transport some goods which have been produced).

However scenarios put into play TO sobriety through changes in the supply chain structure, supply chain philosophy (just on time), routing optimization, changes in urban forms, implementation of last-mile delivery systems, or eco-design of products to reduce packaging size (ADEME, 2014; Association négaWatt, 2014; The Shift Project, 2017; J. Allen & M. Browne, 2010).

The usually considered technologies for modal share are train, road transport (light duty, heavy duty, very heavy duty), or inland navigation. International shipping by boat or plane are usually not considered. Several types of fuels can be imagined for road transport, other than diesel: electrical for light duty or for e-highways trucks (via electric road systems) (European Climate Foundation, 2018); natural gas, hydrogen.

Load rate evolves through more backhauling[11] (ADEME, 2014; J. Allen & M. Browne, 2010).

Finally, energy efficiency hypotheses are taken. These hypotheses can be based on precise expectations on energy efficiency technologies deployment rates (European Climate Foundation, 2018).

4. Industry/agriculture sectors

c. Top-down approach

Energy demand from industrial processes (including energy processes within agriculture) can be assessed through PIB evolution and energy use per unit of economic output (energy intensity).

Economic output depends on offshoring and inshoring (in case the assessment perimeter is geographical) or on imports and exports (if the assessment perimeter is associated with end consumers).

Electricity demand can then be deduced from energy demand evolution by making assumptions on the technology share (new processes using electricity appearing, or processes switching from heat vector to electricity vector). Energy efficiency evolution is exogenously assumed for each industrial processes.

[11] a truck which backhauls transports goods on its way back to its usual loading point / warehouse

d. Bottom-up approach

Another method to assess industrial energy demand is to compute the necessary production of goods and materials in the scenario, based on the hypotheses in the end-consumption sectors (mobility, housing).

Also the part of the goods demand which is produced in the studied territory must be assumed, for example through hypotheses of offshoring or inshoring behaviors of industries.

Then hypotheses on demand sobriety and the STOS are taken: demand sobriety for goods which are deemed useless, stabilization of the sizes of some equipment (size of TV sets), evolution of entertainment appliances (TV sets, boxes, etc.) providing each a greater number of services so less equipment is produced, eco-design (reduction in size and weight of cars...); longer life durations from more maintenance and design standards; reuse of packaging (bottles).

Then specific energy efficiency measures are assumed for each type of process.

G. Climate change impacts long-term energy consumption

The effects of climate change on consumption apply on the total amount of energy consumed per year as well as on the instant power to produce. Peak load may evolve both in terms of magnitude and in terms of periods during the year (see section on power system operation). For example, peak load might increase in hot countries due to increased use of air conditioning, but it might decrease in colder countries due to decreased use of heating.

The most obvious changes on demand are those on weather sensitive demand, such as demand for space heating and cooling. But other changes can be expected, mostly changes related to the adaptation to the impacts of climate change.

Climate change may increase summertime temperatures, in turn increasing demand for air conditioning for buildings. Estimating this increase requires to estimate the temperature increase for different areas and for different periods so as to assess the increase in air conditioning use (more air conditioning devices, which are turned on more often, and use more power because outside air is warmer) (Schweizer & Morgan, 2016). On the other hand, wintertime temperatures may also increase, reducing the need for building heating.

Similarly, the use of air cooling and heating for cars and trucks will be affected by climate change. Also, internal combustion engine economy depends on air temperature: the colder the outside air, the more fuel must be injected into the cylinder at each cycle to provide the same amount of mechanical energy to the wheels (« Heating and Car Mileage », 2009). Hence average consumption of cars and trucks might evolve with climate change.

However, these effects depend on the engine technology which is used: internal combustion engines do not consume more fuel for air heating, as the heat is directly extracted from heat losses in the combustion engine and injected in the passenger compartment. However, they consume more fuel when air cooling is on[12]. On the opposite, electrical cars produce nearly no engine heat loss, hence they consume 10 to 20 % more power for heating or cooling (« Heating and air conditioning in cars », 2019).

Industrial processes also require heating and cooling. Industrial heating and cooling are often neglected in studies about climate change impacts, presumably because the associated temperatures are far from ambient temperatures for many industrial processes. But cold temperatures are actually not so far from ambient temperatures, especially in the food industry (food processing, storage and transportation), hence the associated energy consumption could be considered as dependent on climate change (Hekkenberg, Moll, & Uiterkamp, 2009).

Finally, the efficiency of air conditioners and heaters may depend on the outside air temperature, leading to some nonlinear effects. For example, air conditioners lose efficiency when outside air is too hot and heat pumps lose efficiency when outside air is too cold (Vidalenc, 2018).

[12] From 0.2L to 1L per 100 km (« Heating and air conditioning in cars », 2019)

Fresh water availability might decrease in some regions of Europe due to climate change. Depending on the scenarios, desalination plants might have to be built and to be operated, which requires energy (Schweizer & Morgan, 2016). Fresh water is required for domestic use, for irrigation, for industrial use including power plants cooling, and for leisure activities.

Climate change will affect the frequency and intensity of extreme weather events. Either energy systems[13] are preventively adapted to resist to this novelty or they undergo damages more frequently. In the first case, energy demand increases to build the infrastructure and produce the technologies required for adaptation. For example, energy may be required to build dykes in order to prevent flooding from sea water rise and storms, or to adapt buildings and infrastructure to extreme storms and hurricanes. In the second case, energy demand increases to repair the damages of extreme events, for instance to rebuild dwellings and plants after hurricanes or violent storms, including hail storms, or to pump water after floods.

Even more generally, climate change may also affect human health and the overall biosphere, possibly leading to consume more energy to protect and restore them.

No study to our knowledge integrates in its scenarios the future effects of climate change on demand (nor on production).

(RTE, 2017) integrates in the projections the already observed climate deviation from pre-industrial climate, but does not integrate future deviations. (ADEME, 2015; ADEME / Artelys, 2018) have a similar approach, the climate model being calibrated on 7 observed climate years at the beginning of the 2010's.

As just explained, climate change can have various impacts on demand, depending on the level of climate change, the geographical location of the scenario, and the adaptation measures which are implemented in the scenario. Hence assessing this effect first requires to determine these storyline and perimeter elements.

Recommendations to scenario producers

Scenario producers should make their strategy about climate change consideration on energy demand explicit for all their scenarios.

Specifically, a warning should be introduced for scenarios inducing a significant climate change (as is often the case for business-as-usual scenarios) and which do not assess the effects of this climate change.

If scenario producers decide to consider the effects of climate change on energy demand, they may address the following aspects:

- Climate change and adaptation storylines.
- Effects of the projected climate change on the geographical location of the study, taking into account the adaptation storyline.
- Induced effects on demand for space heating and cooling, in dwellings, tertiary buildings, transport, and industries

Induced effects on demand for other adaptation measures such as desalination or reaction to extreme events

[13] including demand-side, that is, houses, cars, industries and so on

Bibliography

ADEME. (2012). *L'exercice de prospective de l'ADEME - « Vision 2030-2050 »*.

ADEME. (2013). *L'évaluation macroéconomique des visions énergétiques 2030-2050 de l'ADEME - Document technique*. Consulté à l'adresse https://www.ademe.fr/evaluation-macroeconomique-visions-energetiques-2030-2050-lademe-l

ADEME. (2014). *Visions énergie climat 2030/2050 - Quels modes de vie pour demain ?* (Nº 8102; p. 132).

ADEME. (2015). *Un mix électrique 100% renouvelable ? Analyses et optimisations*.

ADEME. (2016). *Potentiels d'extension de la consommation collaborative pour réduire les impacts environnementaux* (p. 23).

ADEME / Artelys. (2018). *Trajectoires d'évolution du mix électrique 2020-2060 - Synthèse*.

Association négaWatt. (2014). *Scénario négaWatt 2011-2050 - Hypothèses et méthode*.

Barker, T., Dagoumas, A., & Rubin, J. (2009). The macroeconomic rebound effect and the world economy. *Energy Efficiency*, *2*(4), 411-427. https://doi.org/10.1007/s12053-009-9053-y

Barton, J., Huang, S., Infield, D., Leach, M., Ogunkunle, D., Torriti, J., & Thomson, M. (2013). The evolution of electricity demand and the role for demand side participation, in buildings and transport. *Energy Policy*, *52*, 85-102. https://doi.org/10.1016/j.enpol.2012.08.040

Bouneau, S. (2018). *Physical and economic analysis of energy transition scenarios - Methodology and first results*. Présenté à Les Houches. Consulté à l'adresse http://science-and-energy.org/wp-content/uploads/2018/03/Bouneau-presentation-Houches-2018.pdf

Briand, Y., Lefevre, J., & Cayla, J.-M. (2017). *PATHWAYS TO DEEP DECARBONIZATION of the passenger transport sector in France*. 37.

Brown, T. W., Bischof-Niemz, T., Blok, K., Breyer, C., Lund, H., & Mathiesen, B. V. (2018). Response to « Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems ». *Renewable and Sustainable Energy Reviews*, *92*, 834-847. https://doi.org/10.1016/j.rser.2018.04.113

Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria. (2012). *Global Energy Assessment - Toward a Sustainable Future*.

David JC MacKay. (2009). *Sustainable energy - Without the hot air* (UIT Cambridge Ltd.).

Demski, C., Thomas, G., Becker, S., Evensen, D., & Pidgeon, N. (2019). Acceptance of energy transitions and policies: Public conceptualisations of energy as a need and basic right in the United Kingdom. *Energy Research & Social Science*, *48*, 33-45. https://doi.org/10.1016/j.erss.2018.09.018

DGEC/CGDD/ADEME. (2015). *Scénarios prospectifs Energie - Climat - Air pour la France à l'horizon 2035*.

E3MLab. (2017). *PRIMES Model, Version 6, 2016-2017 - Detailed model description*.

E3MLab & IIASA. (2016). *Technical report on Member State results of the EUCO policy scenarios* (p. 381).

ECF. (2010). *Roadmap 2050 - A Practical Guide to a Posperous, Low-Carbon Europe*.

ENTSOG/ENTSO-E. (2018). *TYNDP 2018 - ANNEX II: Methodology*.

European Climate Foundation. (2018). *Trucking into a Greener Future: the economic impact of decarbonizing goods vehicles in Europe* (p. 67).

European Commission. (2011). *Energy Roadmap 2050 - Impact assessment and scenario analysis*.

European Commission. (2016). *EU reference scenario 2016: energy, transport and GHG emissions : trends to 2050.* Luxembourg.

Fraunhofer ISE. (2015). *What will the energy transformation cost? - Pathways for transforming the German energy system by 2050*.

Gillingham, K., Kotchen, M. J., Rapson, D. S., & Wagner, G. (2013, janvier 23). Energy policy: The rebound effect is overplayed [Comments and Opinion]. https://doi.org/10.1038/493475a

Graus, W., & Kermeli, K. (2012). *Energy demand projections for Energy [R]evolution 2012* (p. 82). Utrecht University.

Greenpeace. (2012). *Energy [R]evolution - A sustainable world energy outlook 2012* (p. 340).

Greenpeace. (2015). *Energy [R]evolution - A sustainable world energy outlook 2015* (p. 364).

Heating and air conditioning in cars: how much petrol do they consume? (2019). Consulté 29 octobre 2018, à l'adresse Endesa website: https://www.endesaclientes.com/blog/heating-air-conditioning-car

Heating and Car Mileage. (2009, novembre 18). Consulté 29 octobre 2018, à l'adresse A Posteriori website: https://empiricisms.wordpress.com/2009/11/17/heating-and-car-mileage/

Hekkenberg, M., Moll, H. C., & Uiterkamp, A. J. M. S. (2009). Dynamic temperature dependence patterns in future energy demand models in the context of climate change. *Energy*, *34*(11), 1797-1806. https://doi.org/10.1016/j.energy.2009.07.037

IIASA. (2012). Energy Pathways for Sustainable Development. In *Global Energy Assessment Towards a Sustainable Future*.

IPCC. (2007). *Climate Change 2007: Working Group III: Mitigation of Climate Change* (Nº Fourth).

J. Allen, & M. Browne. (2010). *Considering the relationship between freight transport and urban form* (p. 78). University of Westminster.

Keramidas, K., Kitous, A., Schmitz, A., European Commission, & Joint Research Centre. (2017). *POLES-JRC model documentation.*

Ko, Y. (2013). Urban Form and Residential Energy Use: A Review of Design Principles and Research Findings. *Journal of Planning Literature*, *28*(4), 327-351. https://doi.org/10.1177/0885412213491499

Krook-Riekkola, A., Berg, C., Ahlgren, E. O., & Söderholm, P. (2017). Challenges in top-down and bottom-up soft-linking: Lessons from linking a Swedish energy system model with a CGE model. *Energy*, *141*, 803-817. https://doi.org/10.1016/j.energy.2017.09.107

Le Gallic, T., Assoumou, E., & Maïzi, N. (2017). Future demand for energy services through a quantitative approach of lifestyles. *Energy*, *141*, 2613-2627. https://doi.org/10.1016/j.energy.2017.07.065

Loulou, Ri. (2016). *Documentation for the TIMES Model - PART I* (p. 151). Energy Technology Systems Analysis Programme.

Ministère de l'écologie, du développement durable et de l'énergie. (2015). *Stratégie nationale bas-carbone* (p. 208).

Reynès, F., Yeddir-Tamsamani, Y., & Callonnec, G. (2011). Presentation of the Three-ME model: Multi-sector Macroeconomic Model for the Evaluation of Environmental and Energy policy. *Document de Travail de l'OFCE*, 97.

Riahi, K., Dentener, F., Gielen, D., Grubler, A., Jewell, J., Klimont, Z., … Morgan, G. (2012). Energy Pathways for Sustainable Development. In T. B. Johansson, N. Nakicenovic, A. Patwardhan, & L. Gomez-Echeverri (Éd.), *Global Energy Assessment (GEA)* (p. 1205-1306). https://doi.org/10.1017/CBO9780511793677.023

Rickwood, P., Glazebrook, G., & Searle, G. (2008). Urban Structure and Energy—A Review. *Urban Policy and Research*, *26*(1), 57-81. https://doi.org/10.1080/08111140701629886

Roy, J., Dowd, A.-M., Muller, A., Pal, S., Prata, N., & Lemmet, S. (2012). Lifestyles, Well-Being and Energy. In T. B. Johansson, N. Nakicenovic, A. Patwardhan, & L. Gomez-Echeverri (Éd.), *Global Energy Assessment (GEA)* (p. 1527-1548). https://doi.org/10.1017/CBO9780511793677.027

RTE. (2017). *Bilan prévisionnel de l'équilibre offre-demande d'électricité en France*.

Samadi, S., Gröne, M.-C., Schneidewind, U., Luhmann, H.-J., Venjakob, J., & Best, B. (2017). Sufficiency in energy scenario studies: Taking the potential benefits of lifestyle changes into account. *Technological Forecasting and Social Change*, *124*, 126-134. https://doi.org/10.1016/j.techfore.2016.09.013

Schweizer, V. J., & Morgan, M. G. (2016). Bounding US electricity demand in 2050. *Technological Forecasting and Social Change*, *105*, 215-223. https://doi.org/10.1016/j.techfore.2015.09.001

SFEN. (2018). *Le nucléaire français dans le système énergétique européen*.

SLC. (2017). *Diviser par quatre les rejets de CO2 dus à l'énergie : Le scénario Négatep 2017*.

The Shift Project. (2017). *Décarboner la mobilité dans les zones de moyenne densité - Moins de carbone, plus de lien* (p. 118).

The Shift Project. (2018). *Peut-on faire mieux que le tout-voiture électrique en France*.

United Nations, & Statistical Division. (2018). *International recommendations for energy statistics (IRES)*.

van Sluisveld, M. A. E., Martínez, S. H., Daioglou, V., & van Vuuren, D. P. (2016). Exploring the implications of lifestyle change in 2 °C mitigation scenarios using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, *102*, 309-319. https://doi.org/10.1016/j.techfore.2015.08.013

Vidalenc, E. (2018, juillet 27). Perspectives sur la transition énergétique... parfois numérique. Consulté 10 avril 2019, à l'adresse Le blod de Eric VIdalenc website: https://blogs.alternatives-economiques.fr/vidalenc/2018/07/27/canicule-systeme-electrique-et-vulnerabilite

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The Shift Project

The Shift Project, a non-profit organization, is a French think-tank dedicated to informing and influencing the debate on energy transition in Europe. The Shift Project is supported by European companies that want to make the energy transition their strategic priority & by French public funding.

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Lifestyles and consumption behaviors in energy transition scenarios

Technical file #5 – Draft version

Information and recommendations for scenario producers

This document is part of a set of 12 technical files. These files have been produced by *The Shift Project* after one year and a half of research and experts consultations on the different aspects of energy transition and the future studies around these aspects.

Our project, "Power Systems 2050 – Guidelines for design," started in January 2018, with the participation of 10 experts who defined the key subjects which according to them have to be collectively tackled by future studies about the power transition. *The Shift Project* then investigated each of these subjects, consulting in total 40 experts, organizing 4 workshops, and reviewing a large bibliography, including a dozen of future studies about power (and energy) transition at different geographical scales.

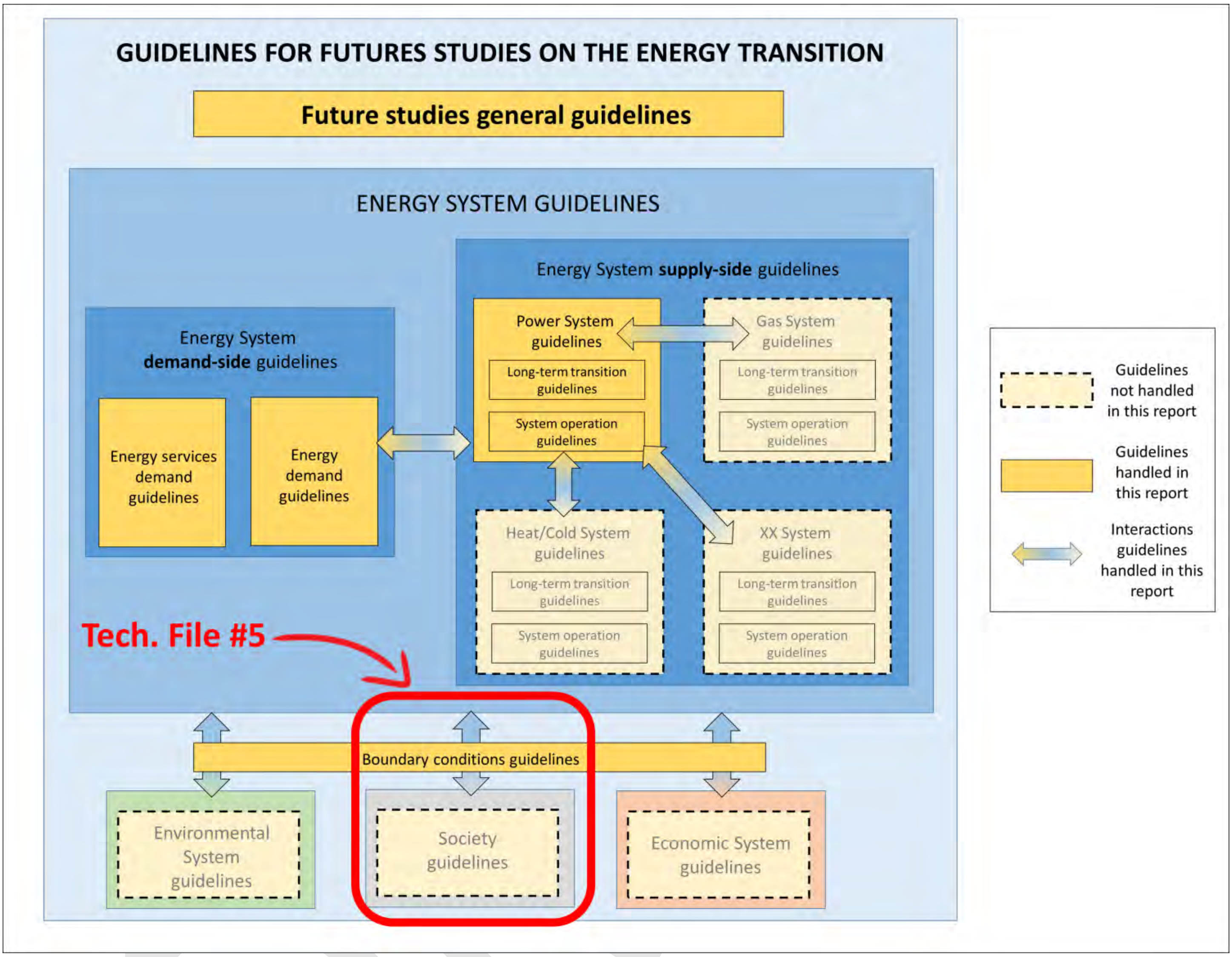
The goal of this project is to produce a set of guidelines addressed to scenario producers. These guidelines seek to foster transparency and consistency *within* future studies and to develop a common language *across* studies. By defining a number of important items which are key to deal with in future studies, we actually propose a study template which enables a better understanding of the location of each proposed scenario on the tree of possible transitions. Once again, the objective is not to *rank* studies, or scenarios, but rather to *compare* them to get a better collective overview of the different aspects of the transition (what are the differences between studies in terms of driving questions, hypotheses, models, methodology, results?).

Several aspects of the energy transition are handled in these technical files. However, on the energy supply-side only the power system has been studied. The main reason for this choice is that we had to start from somewhere with limited resources, and the power system seemed to be a key system to study in the energy transition context, towards a low-carbon economy, as shown by the growing number of future studies focusing on this system. However, the guidelines we propose could be completed by analyzes on the other energy supply-side systems (the gas system, oil system, heat system and so on).

Each technical file tackles several aspects of future studies for the power (and energy) transition. Here is the complete list of the technical files produced during the project:

#	Technical file title
1	Future studies on the energy transition
2	Energy transition models
3	Boundary conditions for energy transition scenarios
4	Long-term evolution of energy consumption in energy transition scenarios
5	Lifestyles and consumption behaviors in energy transition scenarios
6	Long-term evolution of the power system supply-side in energy transition scenarios
7	Power system operation in energy transition scenarios
8	Impact assessment in energy transition scenarios
9	Transition desirability in energy transition scenarios
10	Environmental assessment of energy transition scenarios
11	Economic evaluation of energy transition scenarios
12	Employment assessment of energy transition scenarios

Altogether, these files cover the fields described on the following map of the guidelines for future studies on the energy transition. The document you are reading covers the red-circled topics.



In addition to these technical files, three complementary notes have been produced as specific focuses on the following aspects: material criticality in energy transitions (in French, to be translated and added to technical file #10), levelized cost of electricity (LCOE) in energy transition future studies (in French) and discount rate in energy transition future studies (in French).

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Reading keys

Explanation box, containing key information for a better overall understanding of the subjects.

Recommendations to scenario producers:

These boxes contain the recommendations for scenario producers.

The word "should" means that scenario producers, if they are to follow the guidelines, must substantiate the corresponding point. The words "may" or "might" relates to suggestions, ideas to help the scenario producer respond to the point.

Questions in italic are examples of questions scenario producers might ask to substantiate the points. They are here in an illustration purpose.

Phrases in italic relate to words which are being defined and will be subsequently used in the framework.

Phrases which are highlighted in yellow refer to other technical documents of this series.

There is a strong link between energy system evolution and society evolution.

The first, clear interaction between both systems appears when people negatively reacts when an energy related infrastructure (a new power plant, a new high-voltage line…) is being installed. These reactions have pushed research to study the public acceptance phenomenon: why do people desire, accept, or reject, a project? Too often, scenarios assume that if a technology is cost beneficial it will be readily adopted (Stern, 2017). Section about desirability handles this question.

But further than this aspect, energy is at the core of our lifestyles, having a strong influence on public health, economic inequality, employment, and even social stability and international relations (Stern, 2017). Energy is embedded in our socio-cultural systems, as one may realize when she thinks about the changes brought about by the electrification of our lifestyles (Ruotsalainen, Karjalainen, Child, & Heinonen, 2017), or by the uptake of oil mass production (Auzanneau, 2018).

Some scenarios recognize the importance of the psychological, sociological and cultural determinants of demand (IIASA, 2012), which complements the usual technical and economical approaches. Integrating lifestyle and behavior considerations in energy transition scenarios makes them more robust to social reality, and provides useful tools for decision makers to understand the social risks associated with a scenario.

A. Main aspects of consumption behaviors: lifestyles and inertia

1. Lifestyles and consumption behaviors are deeply interwined

The notion of lifestyle is ill-defined but relates to "our ways of "doing", "having", "using" and "displaying", our behavior and all of the related products, objects and infrastructures. They are marked by our relationships to time, to space, to others, and to ourselves" (Le Gallic, Assoumou, & Maïzi, 2017).

Lifestyle is often evoked as linked to, or as a determinant of, consumption behaviors. Lifestyles "contain a set of key determinants of mobility, housing, spatial planning or the organization terms of the productive sectors (industry, agriculture, services). They thus constitute a fundamental component of direct and indirect energy consumption" (Le Gallic et al., 2017).

"Energy services demand is determined by needs and preferences for multiple services, which in turn depend on, in addition to income level and prices, home country characteristics, dwelling area and type, job and leisure activities, diet preferences, cultural context, religion, etc. A certain lifestyle is characterized by a bundle of these determinants combined with a more or less explicitly framed worldview, a set of values and convictions, preferences, and behaviors. (IIASA, 2012)"

Concretely, the concept of lifestyle is used through typologies. Most proposed typologies are developed along two broad types of dimensions: the first type gathers the aspects pertaining to the environment in which the individual lives, such as her physical environment (dwelling area and type, home country geographical and climate characteristics…) and social environment (people the individual gets along with for example colleagues, friends, family members) and economic resources (income level and prices, savings). The second type gathers the aspects pertaining to more subjective, less concrete, concepts such as values, cultural capital, or life objectives (Tabbone, 2017).

Pragmatically, we consider here that the first dimension (social, physical, economic contexts) represents the different aspects of the present context whereas the second dimension (values, cultural capital…) represents an internalization of the past environment of the individual, that is, a more or less conscious memorization of past experiences which still influence current practices, intertwined with an expression of her inner tastes (Baum, 2016a, 2016c).

In that sense, lifestyles can be said to determine consumption behaviors: the present context (physical, social, economic, institutional…) influences consumption for example through prices, advertisement, imitation of significant others, marketing, physical accessibility[1] and so on; past experiences with consumption also influence present consumption, through learning how fulfilling a product, or a service is on the short and long run, through past

[1] Some products or services may be more accessible in urban areas than in rural ones, in summer than in winter, and so on.

reactions of significant others to one's consumption and so on (these learning effect are sometimes called "brand attachment" when their outcome is positive for the product, or service).

The other way round, "material goods are important to us, not just for their functional uses, but because they play vital symbolic roles in our lives. This symbolic role of consumer goods facilitates a range of complex, deeply engrained 'social conversations' about status, identity, social cohesion, group norms and the pursuit of personal and cultural meaning. In the words of Mary Douglas (1976) 'An individual's main objective in consumption is to help create the social world and to find a credible place in it'" (Jackson, 2005). Hence lifestyles can be said to be influenced by the results of these consumption behaviors. For example, the use of an acquired good can trigger positive reactions from a group of people the individual wants to, or already, belong to, acting as a positive mirror and reinforcing the type of consumption and lifestyle shared within this group of people.

In a word, lifestyles and consumption behaviors co-evolve.

2. Some behaviors require more time to evolve than others: behavioral inertia is a key determinant of transition desirability

Two aspects of this co-evolution are key for our understanding of energy services demand: diversity of lifestyles among a population, and inertia.

Diversity of lifestyles is inherent to the concept of lifestyle, which is mostly applied at the individual level (Tabbone, 2017).

The inertia of the co-evolving couple "lifestyle and consumption behaviors" is often talked about in terms of "identity", "values", "convictions", "social norms", such as in (Bögel & Upham, 2018; Martin & Gaspard, 2016; Roy et al., 2012). These factors of inertia are said to be "internalized". They are deeply rooted in individuals as they emerge and build up from an early age, through social interactions with significant others, local community and society as a whole, including parenting and education. They are also generally shared, and maintained, by a large number of individuals through social norms and cultural traits. Hence they represent high inertia aspects of individuals' behaviors and thoughts.

Some behaviors driven by inertia are sometimes described as "habits, routines and automaticity" by cognitive psychology (Jackson, 2005), in the sense they have been acquired within a context which might have changed since then, but they are not questioned yet. Habits and routines can be said to be partly driven by deeper values, convictions and so on, and partly by more short-term considerations (fashion, prices…). In that sense, some habits and routines present a lower inertia than values, convictions or social norms.

Behavior inertia also occurs through the architecture of incentive structures, including institutional barriers, inequalities in access and restricted choice for consumption behaviors (Jackson, 2005). The physical environment (homes, urban planning, artefacts such as tools and technologies…) is also a source of inertia, shaping and maintaining lifestyles (Martin & Gaspard, 2016).

Changes in lifestyles thus require a sustained change in the environment of individuals, whether it be their physical, social or economic environments. On the medium term, such changes eventually get internalized and build up into new shared values.

High inertia behaviors are those behaviors which are very slow to change. They correspond to more rooted behaviors, such as behaviors linked to convictions, values, identity. If such behaviors are required to change in a fast way, this may lead to desirability issues. This situation much resembles that of stranded assets: because the transition is too fast, some assets become useless and their value is lost. Some values and convictions, in a fast transition, may become useless or go against what would be required to do by the transition. This produces psychological pain, frustrations, and may lead to aggressive behaviors.

3. Different roles in the same individual embed different inertias

Individuals play roles other than their consumer's roles. Each role embeds a certain amount of behavioral inertia. For example, professional skills are a major source of inertia for employees because acquiring new skills (that is, new behaviors and ways of thinking in the professional setting) takes time, all the more in economies based on labor division into highly specialized jobs (requiring up to several years of training) (Bögel & Upham, 2018) (also see Jobs section). Similarly, "society decision-makers" have a certain amount of inertia in the ways they make-up their decisions, would it be citizens as voters or as elected representatives or participants in social organizations. Note that the inertia of the latter role (society decision-maker) does not interest future studies, as they aim at influencing this role rather than modelling it. "Business decision-makers" (board of directors and business executives) have a certain amount of inertia, which is partly modelled in simulated agents studies. For example, PRIMES model, or the model used by RTE model investment decisions based on assumptions on technology maturity and associated risks (E3Modelling, 2018; RTE, 2017).

B. Collectively speaking, scenarios little address the question of behavior change

1. Most scenarios do not consider behavior change during transitions

Often, scenarios just assume lifestyles changes without explaining how they happen. Behavior change is not seen as a lever nor as a constraint. It is simply ignored. Assumedly, if technique and economic viability is ensured, then people will accept to change their behaviors and accept the installation of new infrastructures.

Future studies can be separated into two broad groups regarding lifestyles:

- The *lifestyle-mute studies*, in which no concrete information is provided about lifestyle evolutions. In those studies (such as (ADEME / Artelys, 2018; CGDD, 2016; RTE, 2017; Barton et al., 2013)), it is difficult for the reader to imagine what the lifestyles would look like. This does not come as an issue for scenarios in which lifestyles little evolve, but may trigger desirability questions for scenarios in which lifestyles significantly evolve. By being largely mute about lifestyles, these studies do not address the key issue of desirability.
- The *lifestyle-as-usual studies*, which assume no lifestyles changes happen but those induced by market mechanisms. Those changes always happen under "easy" situations, such as a GDP steadily increasing over the scenario timeframe, energy service technologies continuously improving and a better information being provided about the products (De Vita et al., 2016; E3MLab & IIASA, 2016; ECF, 2010; European Commission, 2011; Fraunhofer ISE, 2015; Lappeenranta University of Technology / Energy Watch Group, 2017). Note that these studies are also largely mute about lifestyles, because they implicitly consider the few behavior changes they describe are largely desirable. In those cases, individuals are assumed to get equipped with more energy-efficient technologies through effortless consumption behaviors, such as investing in house insulation, or getting a more fuel-efficient car. In other words, no consumption behavior change is assumed as individuals keep thinking in an economically "rational" way and keep the same preferences during the whole scenario timeframe: only the release of more efficient technologies, and the changes in relative prices, trigger changes in bought products towards the most rational choice. Individuals are either modeled as consumers[2] through the "*rational choice model* which assumes they make decisions by calculating the individual costs and benefits of the different courses of action and choosing the option that maximizes their expected net benefits" (Jackson, 2005); or they are not modeled at all and a storyline about energy efficiency of energy service equipment is provided. In both cases, individuals are not described as engaging in more energy-sufficient behaviors. In those studies, (nearly) perfect markets are the main drivers of the transition, with the help of engineering improvements towards more efficient technologies. These markets have nonetheless to be equipped with a way to internalize the externalities which are deemed unacceptable, as private decisions do not always take account of social costs. This is why those scenarios implement a carbon price, which does curb consumption behaviors towards low-carbon technologies along the scenario timeframe. However, those behaviors changes are not concretely described and their desirability is not discussed. The second and last lever which is used in those scenarios to change behaviors is a better information about products, such as their efficiency, their carbon content and so on (Jackson, 2005).

[2] Generally, one representative macro consumer, with different techniques to simulate a distribution of different behaviors around the behavior of the macro consumer. The macro consumer has predetermined and stable preferences, which are assumed not the be determined by the social or institutional contexts (Jackson, 2005).

- A few studies go further than imagining no changes in lifestyles by detecting emerging behavioral trends and assuming they keep going, such as Vision 2030 by ADEME which assumes the continuation of shared mobility trends and more health-oriented food habits (ADEME, 2012).
- The *lifestyle-transformational studies*, which assume significant changes in lifestyles happen towards energy-sufficiency in addition to changes in energy efficiency of energy service equipment such as Vision 2050 by ADEME or négaWatt scenario (ADEME, 2012; Association négaWatt, 2014). In those studies, the desirability of behavior changes are sometimes substantiated through a technical storyline, and sometimes not substantiated. Behavior changes are sometimes merely assumed, and sometimes they are linked to the implementation of policies. In (The Shift Project, Kahraman, Guérin, & Jancovici, 2017), which is also lifestyle-transformational, the possible impacts in terms of desirability of the proposed transition are described for different actors (households, corporates).

As just shown, apart from lifestyle-transformational scenarios, studies and scenarios assume no lifestyle changes, or they explain the few behavior changes through unconstrained and natural changes in the average personal preferences. In the latter case, policy makers are assumed to react to the new, emerging social norms (such as a "heightened environmental consciousness"), as opposed to triggering and fostering them (Samadi et al., 2017). Most often, values and other inertial behavior components are implicitly considered as part of the most unalterable elements of the described world[3] (Bögel & Upham, 2018) and as such are assumed to remain in line with current lifestyles. This may lead scenario readers, including decision makers, to believe that no measures can be taken to promote energy consumption decrease, or that such measures are not needed (Samadi et al., 2017).

2. In reality, behaviors can and do change

However, behavior science has extensively shown that behaviors do change during one's lifetime and has explained the reasons for the changes in large parts (see box below). Theoretically, two broad types of political levers account for significant behavior changes (Samadi et al., 2017):

- Modification of relative prices, comfort, or any other preference criteria between several activities through policy levers. For example, reducing car speed modifies the relative speed between car and public transportation, fostering a modal shift from car to other modes. (possible feeling of coercion)
- Politically imposed bans or limits (possible feeling of coercion)

In addition, other causes than political levers may lead to behavior changes and modifications of preferences. From a political point of view, it can be said to happen through politically unguided culture evolution. We call this type of behavior change the *"no lever" behavior change*. Such cultural tendencies, mostly expressed within the social environment, influence the effectiveness of political levers because changing habits is much easier in a supportive, social environment (Jackson, 2005).

3. The type of models used by lifestyle-as-usual future studies explains why they consider behavior change so little

The rational choice model assumes consumption behaviors follow optimization rules which do not evolve through time (as consumer preferences do not evolve). Hence behaviors evolutions cannot be studied, or projected with such a model. There exists other types of behavior models, which account for the fact that "human behaviors are not purely rational and self-interested". For example, these models take into account the following:

- Habits, routines and automaticity in our behaviors. These patterns illustrate what the rational choice model would consider as "suboptimal" behavioral inertia and that it would avoid through "better information." Indeed many frequent, routine behaviors do not call for a deliberation anymore after they have been tested out several times and their consequences are known by the individual, even though they might not be optimal anymore because conditions changed. They are nonetheless very useful rules of thumb for not spending energy into endless deliberation before each behavior.
- "Our preferences are largely dependent on social and interpersonal factors" (Jackson, 2005). This implies that these preferences can change not only within individuals during one's lifetime but also within a

[3] These inertial elements are called "landscape level" in the Multi-level perspective of transition.

whole culture[4]. Preferences apply largely on non-commensurable commodities (that is, commodities which cannot be measured under the same unit because they are different in essence, such as health, safety, comfort, speed and so on), making the evolution of their relative weights in a "utility function" difficult to understand in terms of cultural changes and as a consequence difficult to tune.

These alternative behavior models are not used by scenario producers, even though they could provide more diversity across studies in hypotheses about lifestyles.

4. A collective lack: scenario production should fully integrate social sciences instead of being mostly driven by engineers and economists

Part of the issue comes from the fact that evolutions of lifestyles are mostly studied by social sciences but results from this field are rarely included in future studies (Hache & Palle, 2018). Future studies are largely led by economists teams, which more readily use the rational choice model or by engineers teams which consider the technical aspect of the transition; sociologists, or behavior scientists are poorly, inadequately (e.g. too late in the scenario production process), or not at all included in the future studies teams.

The exclusion of behavior scientists from scenario production lead to two main risks for the scenario community as a whole:

- Ignoring interesting political and economic levers (such as public investment in infrastructures, bans, imposed standards and so on), by focusing only on market-based levers. This is one collective shortcoming for studies using the rational choice model. As a result of this collective ignorance by future studies, scenario readers, including decision makers, may conclude that measures promoting non-market levers (such as energy-sufficient lifestyles) are not efficient, not available or even detrimental for society (Samadi et al., 2017).
- On the opposite, underestimating behavioral inertia and hence overestimating behavioral changes' speed. This bias is equivalent to neglecting some non-desirability issues induced by the speed of change. Such a bias may appear in lifestyle-transformational scenarios when strong assumptions on behavior changes are made. E.g., some scenarios assume mass building insulation without dealing with the subject of desirability of the investment decision and of the works.
  Surprisingly, this bias can also appear in lifestyle-as-usual scenarios when they implement a strong carbon price: in this case consumption behaviors change unrealistically fluently under the effect of the carbon price (implicitly assuming this effect, called "disutility,"[5] is deemed desirable by citizens) (E3MLab, 2017). However, in lifestyle-as-usual scenarios, individuals are usually supposed to live in wealthy situations (GDP is assumed to grow) and they can easily afford more expensive, more efficient, and lower carbon technologies so that the induced disutility might be argued to be acceptable.

As a conclusion, when a collective look is taken at published future studies, either behavior changes are not considered at all (true for most scenarios using the rational choice model), or they are assumed to change fluently and naturally. When behavior change occurs in scenarios, no account is provided for the expected changes and no political lever is proposed except for a few exceptions ((Association négaWatt, 2014; The Shift Project et al., 2017) and some aspects of Vision 2050 (ADEME, 2012)). As a result, costs associated to behavior changes are not taken into account (sometimes referred as transition costs).

[4] Equivalently, the "distribution of preferences" might significantly evolve within a population.
[5] Disutility is an assessment of the utility loss compared to a situation in which the constraint does not exist. It is concretely composed of buying more expensive technologies, paying for more expensive energy, and consuming less in some sectors due to this buying more expensive goods and services, all those effects being in comparison to a situation without (carbon) constraint.

Recommendations to scenario producers

Scenario producers should make their strategy about behavior change explicit. In case they chose not to address this question, they should substantiate the fact that this choice does not hide desirability issues.

If behaviors change in a scenario, the reasons for the changes should be made explicit. The following reasons may be considered: no-lever change, or political levers activations.

Scenario producers should report the way they consulted social sciences in the course of the study: who they got in touch with, or what social sciences sources they resorted to, in what ways, and at what points in time during the study.

Good practices include:

the study of lifestyles should be an integrated part of the process of scenario production. Social scientists, such as sociologists or psychologists should be involved at the very beginning of the process and remain part of the team during the whole process. Their role is to inform scenario producers

- about the implications of their hypotheses during the storyline definition
- about the implications of their results during the interpretation of results

C. Curving cultural trend is difficult in reality: transformational scenarios should address desirability issues

1. Changing behaviors may require time and lead to desirability issues

Understanding cultural trends (new, emerging ones as well as solidly rooted ones) and their translation into consumption behaviors is key for producing behavior-transformational scenarios.

The more social norms are shared and associated with a strong social punishment in case of deviation from them, the more difficult to change they are. Body hygiene, eating and drinking habits or dwelling habits are examples of behaviors whose trends are difficult to change. For example, constraining dwelling surface per inhabitant may be a real challenge. They are anthropologic realities which evolve little and slowly (Martin & Gaspard, 2016). Hence cultural trends are socially shared behavior patterns which have a certain inertia.

If such trends are to be changed through judiciary norms, the costs to enforce the new trends through coercion means can be extremely significant. They can include mass monitoring of individuals' behaviors and means to punish deviations from the new trend as systematically as possible. In case coercion power is limited, new judiciary norms must be first accepted within large parts of the population (Martin & Gaspard, 2016). By and large, this fact legitimates the idea that proposed transitions should be desirable. This concept is developed in the desirability section. In other words, the social body should not be considered as an adjustment variable, as it is not necessarily more flexible than the built environment.

2. Detecting cultural trends is complex but improves storyline design by rooting it in the current culture

Understanding and monitoring cultural trends is complex and requires a certain amount of data. Indeed, different groups of people can exhibit different cultural trends, as a function of their characteristics, such as: their revenue level, their age, their gender, the type of urban tissue they live in, their working status (unemployment, retirement, etc.), their rural or urban lifestyle, their household structure (number of children, are the parents together, how many persons of the same family are living in the house, etc.), information about their housing context (owner or tenant status, house or apartment, suburb or city-center, metropole or village, etc.), their attitude towards environment. These are factors which can highlight some cultural trends in some domains. For example, younger generations in developed countries are less attracted to owning, or using a car than older generations.

Some "no-lever" cultural changes can be noticed in developed countries such as France. Here are examples of some of them, applying to small, but growing, portions of the population:

- Regional, or local governance is preferred. The emergence of this preference is accompanied by a loss of trust in national governance.
- Preference towards more energy autonomy/autarchy
- New collaborative and local investment practices (local crowdfundings) (Hache & Palle, 2018)
- Small project size in electricity supply (OECD/IEA, 2017)
- Buying bigger and more powerful cars (Sport Utility Vehicles, SUV) for buyers of new cars in France (Chassignet, 2019).
- Meat consumption reduction in younger generations (ADEME/CREDOC/RDC Environment, 2015)
- Attachment to material goods and strength of habits for people above 40 year-old (ADEME/CREDOC/RDC Environment, 2015)

Recommendations for scenario producers

Scenarios should make their strategy about cultural trends consideration explicit.

If they are considered, a description of the observed and expected trends should be provided for the studied geographical perimeter.

If observed cultural trends are curved in a scenario, discussion about the inertia of those trends as well as the levers which are used to curve them should be provided. Inertia should be assessed with regards to how shared the trends are and how associated to a social punishment in case of deviation from them they are. In case of high inertia, considerations on desirability of these changes should be made (see desirability section).

For example, if the scenario assumes the trend towards new energy production and consumption structures (local production, short supply chains, etc) reverses back to a centralizing trend, this reversal should be explained in a narrative.

For example, in France, the trend is currently that people have greater and greater living area. Hence scenarios assuming a reduction, or stabilization of the living area per inhabitant should warn about this trend discontinuity.

The evolutions of lifestyle during the timeframe of a scenario should be described.

Lifestyle evolutions should be qualitatively described for a few highly contrasted household categories.

D. Detailed considerations on policy levers and their effects on behavior changes during transitions

We now develop some ideas about the different levers on behaviors, such as the different useful levels at which they can be thought out, the main different types of levers available to policy-makers, and some considerations on the way they should be activated for more efficiency and desirability.

Levers to change behaviors have been extensively studied by behavior analysis

The science called behavior analysis have extensively studied the determinants of behavioral changes. Along the view of behaviorism, the philosophy associated with behavior analysis, changing behaviors is equivalent to changing the determinants of behaviors.

Here are the main findings of this science on behaviors (summarized from (Baum, 2016b)):

Human behaviors are determined by what has been called 3-terms contingencies, and which corresponds to *incentive feedback loops* (increasing the occurrence of behaviors under the incentive) and *constraint feedback loops* (decreasing the occurrence of behaviors under the constraint). Incentive feedback loops provide rewards when the behavior considered as appropriate happens. Short-term rewards include smiles, nice words, or money and in the long-term diplomas, a rewarding job, good health, rewarding relationships, and more globally a rewarding environment. Constraint feedback loops produce punishment when the behavior considered as inappropriate happens. Punishment include in the short-term cold or angry reactions by others or fines, and in the longer-term, lawsuits, imprisonment, a lack of, or negative relationships, bad health and more globally a difficult to live environment.

The better these feedback loops are known (through communication campaign, through imitation of others knowing these feedback loops, through mouth-to-hear tips, advice…), the more easily individuals can engage in preferred, more rewarding feedback loops.

These feedback loops, to have a lasting effect on behaviors, must themselves remain stable.

The more probable and systematic the consequences of these feedback loops are, the more efficient they are to change behavior and maintain novel behavior.

The faster the consequence of the feedback loop after the occurrence of the behavior, the more efficient the feedback loop.

1. Behaviors are under the influence of several *influence levels*: close relationships, society and the physical environment

Behaviors evolve, and are maintained, by incentives and constraints applying to them. Several levels of incentives and constraints apply on individuals. Here are the three influence levels usefully framing discussions about levers on behaviors:

- People closely related to the individual (such as family members, friends, colleagues, neighbors…) produce incentives and constraints through their interactions with the individual. They influence one's behaviors through advice, tips, education (for children within the family), exemplification followed through imitation…
- society as a whole (including institutions, economic rules and economic structure, justice, social norms…). Economic structure directly influences our behaviors through the services it proposes, as well as indirectly via our physical environment, through the goods it produces. It also influences our behaviors through advertisement ("information campaigns") (IIASA, 2012). Business practices can also influence the behaviors of their employees. Institutions influence our behaviors through the taxes, subsidies, bans and so on they implement and enforce through administration, police, justice etc.
- the physical environment (such as infrastructures, technologies and tools). It most directly influences our behaviors and also constitutes an element of inertia (see future studies).

To be as efficient as possible, measures towards behavior changes should implement incentives and constraints on all those aspects. However, policies are best applicable on society as a whole (laws, bans, taxes and subsidies…) and on the physical environment, directly through design and building of public spaces, and indirectly through production standards for the technologies and tools individuals use. As was explained above, levers on society as a whole can be implemented only if they are deemed acceptable, that is, only if they are largely accepted at the small group level.

2. Policy makers have access to four *policy levers* to change behaviors

These different levels can be derived into four different policy levers to change behaviors (Martin & Gaspard, 2016).

- Communication and information tools, including individual counselling or group support. They aim at informing about the existence of alternative behaviors or about the pros and cons of each alternative. They can also aim at altering the perceptions on these pros and cons. Examples include consumption labelling for appliances or cars or communication campaigns about car accidents for speed limits enforcement. Exemplifying the desired changes within State's own policies and practices also belongs to communication tools (Jackson, 2005).
- Infrastructure tools, aiming at providing new possibilities for alternative behaviors, by providing new goods or services, or at making more difficult former behaviors. Examples include new cycling or pedestrian infrastructure or city planning to reduce trip distances or car use. Infrastructure and public space design can have an influence on behaviors with so-called "nudges". However, this technique has a more anecdotal

and less sustainable effect since they seek to modify behaviors without individual knowledge building: with this technique individuals change their behaviors sometimes without knowing why they should do so.

- Economic tools (taxes and subsidies). They aim at modifying the relative weights of pros and cons between alternative behaviors. Examples include purchase taxes depending on the fuel consumption of cars, or subsidies to reduce public transportation price. Subsidies towards specific fields of research, such as specific technologies or tools, can also lead on the medium-term to changes in the physical environment, which is in part composed of the technologies and tools we use.
- Legal tools (obligation or ban, standards). They also aim at modifying the relative weights of pros and cons between alternative behaviors, through coercion. Examples include car bans in some parts of cities, speed limits for vehicles, or emission standards for cars. It also includes standards for companies leading to producing products with novel characteristics, which in turn end up in individuals' physical environment as new available technologies and tools. It also includes laws to promote novel behaviors among employees, such as changing commuting trips.

3. The ways policy packages are framed is key for efficiency and desirability: the *lever activation modes*

For more efficiency of the levers, the following aspects are key (Bögel & Upham, 2018). We call them the four *lever activation modes*.

- Ability to adopt: As previously mentioned, behavior changes happen much more easily when they are deemed acceptable, that is, when they are already shared and largely encouraged within portions of the population. In other words, some form of knowledge and emerging cultural norms should be present to enable behavior change. Many scenarios evoke an environmental consciousness to explain the adoption of novel, eco-friendly behaviors in a "no-lever" way.
- Tailored approach: several levers should be activated together and in a consistent way, that is, they should clearly all direct towards a limited set of behaviors, as opposed to directing towards novel behaviors and former behaviors at the same time. Generally speaking, goods and services providers invest large amounts of money in marketing and advertisement, contributing to shape shared cultural norms directing behaviors towards consuming those goods and services (Martin & Gaspard, 2016), which may go against measures implemented in transformational scenarios. This illustrates how incentives and constraints in place can be contradictory and lead to desirability issues.
  Ideally, levers should be activated along all the mentioned levels (small groups of close relationships, society and the physical environment).
  Different types of levers should be activated together for each targeted behavior:
  - push measures (that is, incentive feedback loops promoting the novel behavior)
  - pull measures (that is, constraint feedback loops constraining the former behavior)
  - information campaign *if needed to inform about the presence of the new feedback loops*. Note that the information campaign informs about the novel situation (shaped by the new pull and push measures) in which behaviors take place. On the contrary, leading an information campaign about the existing situation without any new push or pull measure have little chance to be efficient if its goal is to signal the presence of opportunities that people assumedly (in a collective way) have not understood or seen the presence of opportunities around them. "Information campaigns have been widely used for achieving public interest goals. But they are known to be less effective than other forms of learning. Research suggests that learning by trial and error, observing how others behave and modelling our behavior on what we see around us provide more effective and more promising avenues for changing behaviors than information and awareness campaigns" (Jackson, 2005).
- Continuous priming: Behavior changes cannot be maintained by sole information, even continuous information. Context has to evolve and be sustained in its novel state to maintain new behaviors. This applies to all the mentioned levers (infrastructure, economic incentives and so on).
- Extent: Information and context changes lead to behavior changes more readily if they target behaviors with direct consequences on the individual than if behavior consequences are further away in space, time, and probability. For example, parking ban in some places is more efficient if it systematically and quickly enforced. Energy use is more easily reduced if it is directly monitored and displayed to the consumer. On the contrary, far ahead consequences of climate change have less effects on behaviors. Communication campaigns may be useful to act on the extent aspect of levers, by presenting the long-term consequences of a behavior in order to make them more concrete so that individuals better take them into account. For example, communication campaigns could highlight the links between some behaviors and climate impacts.

Introducing and sustaining lifestyle change is thus not as straightforward as a (prescriptive) modeling approach may suggest. The design of a successful policy strategy requires knowledge of all these factors that determine and sustain changes in specific behaviors.

4. Different behavior changes require different levers

a. The specific case of investment decisions

Social sciences for energy has mostly studied changes in daily behaviors as opposed to household decisions to invest in insulation, or other investment decisions, even though such decisions can be more powerful at changing energy consumption (Stern, 2017).

Indeed, it has been noticed that behaviors characterized as *investment* behaviors are much closer to those assumed in the rational choice model. For example, energy is most commonly framed as a basic need by individuals, except when they consider investment decisions in energy savings: in this situation, they frame energy as a commodity, with considerations on return on investment and cost reductions (Demski, Thomas, Becker, Evensen, & Pidgeon, 2019). For this category of behaviors, economic incentives are key, as well as knowledge about the investment opportunity and its consequences (in terms of savings, comfort and so on). Hence favorable enough[6] economic incentives and a communication campaign about them is likely to be efficient to direct household's investment.

Other levers may be more adapted in the case of daily consumption behaviors, which are most often habitual (Bögel & Upham, 2018). "A vital ingredient for changing habits is to 'unfreeze' existing behavior - to raise the behaviour from the level of practical to discursive consciousness." And as for any other behavior change, "this process is known to be more effective in a supportive, social environment" (action at the small group level) (Jackson, 2005).

Hence the targeted influencing levels, the selected policy levers, and the lever activation modes will certainly be different for these two types of behaviors.

b. Practical case: changing "car buying" behaviors

As an example, we consider here the case of car buying. Let us consider the different levels of incentives which apply to individuals when they buy a car, and enumerate the different incentive feedback loops probably applying:

- The physical environment: public spaces are greatly designed for car use, through a very dense and well maintain road network, with a high speed road network. City planning and activity location often requires the use of a car to have access to basic services and resources as well as to activities required to live a decent life and to stand one's role for society (access to work, to schools for children, to healthcare…). Also influencing the physical environment, standards and bans from the State affect the type and characteristics of cars which are accessible to buying.
- Society as a whole:
    - Economic system: several services are proposed everywhere on the territory for car owners, such as garages and insurances. The economic system also largely implements communication campaigns (advertisement) associating car ownership to long-term rewards, such as high social positions, positive relationships (love relationships, friendship, family…), and socially highly-valued activities (traveling, taking care of one's family…).
    - Institutions, through taxes and subsidies, as well as costs induced by car ownership (insurance, maintenance…) impact car buying.
- Small groups of close relationships: the type of car that close relationships own and the way they use it, as well as what they say about it also have an influence on car buying.

If car buying behaviors are to be changed (for example, towards less powerful cars, or towards low-carbon cars, or even towards buying less cars), then incentives and constraints around car buying must be altered in the desired way. However, they must be so in a sustained way (stability of a novel built environment and city planning, stability of price incentives…) to change behaviors and maintain novel behaviors. Plus, the overall set of incentives and constraints must be readable and consistent. For example, modifying taxes and subsidies (e.g. taxes for owning a powerful car and subsidies for replacing one's car by bikes…), or the built environment (less space for car flows

[6] Considering the specific economic situation of the different households

and for parking) without modifying advertisement for powerful cars decreases the probability to change behaviors compared to a no advertisement situation. Furthermore, such discrepancies can lead to discontent (see desirability section).

Recommendations to scenario producers

Behavior changes should be explained. For each behavior change, a narrative about the following aspects should be developed:

- The policy levers which are activated:
    - communication and information tools. For example: *What kind of communication campaign? Is exemplification used? What changes in labelling practices?*
    - infrastructure tools. For example: what changes in urban planning? What new transport infrastructure?
    - economic tools (taxes and subsidies). For example: *what activities are more taxed/ more subsidized? For what actors? Are CO2 emissions taxed, and with which tool? For who? Are some research fields subsidized?*
    - legal tools (obligation or ban, standards). For example: *what activities are banned? Is driving in city centers banned? Are there car production standards imposed?*
- The lever activation modes which are used:
    - ability to adopt: *why would actors accept the proposed levers?*
    - tailored approach. For each behavior change, push measures, pull measures and in some cases, information campaigns, should be considered. Internal consistency of the whole policy package, as well as consistency with the other incentives and constraints in place, should be considered, for the different actors and with regards to the different targeted behaviors within the scenario. *For example: is advertisement based on the price indicator still allowed when new labelling seek to promote other indicators such as energy consumption and CO2 emissions?*
    - continuous priming. *How are the proposed measures sustained during a long-enough time?*
    - extent. Do the proposed measures implement incentive / constraint feedback loops which directly act on the targeted behaviors? If not, considerations on the efficiency of the lever should be provided.

For all the impact assessments which are performed in the study, the impacts of the levers which are activated should be taken into account within the considered impact inventory.

Bibliography

ADEME. (2012). *L'exercice de prospective de l'ADEME - « Vision 2030-2050 »*.

ADEME. (2013). *L'évaluation macroéconomique des visions énergétiques 2030-2050 de l'ADEME - Document technique*. Consulté à l'adresse https://www.ademe.fr/evaluation-macroeconomique-visions-energetiques-2030-2050-lademe-l

ADEME. (2014). *Visions énergie climat 2030/2050 - Quels modes de vie pour demain ?* (No. 8102) (p. 132).

ADEME. (2015). *Un mix électrique 100% renouvelable ? Analyses et optimisations*.

ADEME / Artelys. (2018). *Trajectoires d'évolution du mix électrique 2020-2060 - Synthèse*.

Association négaWatt. (2014). *Scénario négaWatt 2011-2050 - Hypothèses et méthode*.

Barton, J., Huang, S., Infield, D., Leach, M., Ogunkunle, D., Torriti, J., & Thomson, M. (2013). The evolution of electricity demand and the role for demand side participation, in buildings and transport. *Energy Policy*, *52*, 85-102. https://doi.org/10.1016/j.enpol.2012.08.040

Bouneau, S. (2018). *Physical and economic analysis of energy transition scenarios - Methodology and first results*. Les Houches. Consulté à l'adresse http://science-and-energy.org/wp-content/uploads/2018/03/Bouneau-presentation-Houches-2018.pdf

Brown, T. W., Bischof-Niemz, T., Blok, K., Breyer, C., Lund, H., & Mathiesen, B. V. (2018). Response to « Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems ». *Renewable and Sustainable Energy Reviews*, *92*, 834-847. https://doi.org/10.1016/j.rser.2018.04.113

David JC MacKay. (2009). *Sustainable energy - Without the hot air* (UIT Cambridge Ltd.).

De Vita, A., Tasios, N., Evangelopoulou, S., Forsell, N., Fragiadakis, K., Fragkos, P., … Directorate General for Mobility and Transport. (2016). *EU reference scenario 2016: energy, transport and GHG emissions : trends to 2050.* Luxembourg: Publications Office.

Demski, C., Thomas, G., Becker, S., Evensen, D., & Pidgeon, N. (2019). Acceptance of energy transitions and policies: Public conceptualisations of energy as a need and basic right in the United Kingdom. *Energy Research & Social Science*, *48*, 33-45. https://doi.org/10.1016/j.erss.2018.09.018

DGEC/CGDD/ADEME. (2015). *Scénarios prospectifs Energie - Climat - Air pour la France à l'horizon 2035*.

E3MLab. (2017). *PRIMES Model, Version 6, 2016-2017 - Detailed model description*.

E3MLab & IIASA. (2016). *Technical report on Member State results of the EUCO policy scenarios* (p. 381).

Energy Technology Systems Analysis Programme. (2016). *Documentation for the TIMES Model*.

ENTSOG/ENTSO-E. (2018). *TYNDP 2018 - ANNEX II: Methodology*.

European Climate Foundation. (2018). *Trucking into a Greener Future: the economic impact of decarbonizing goods vehicles in Europe* (p. 67).

European Commission. (2011). *Energy Roadmap 2050 - Impact assessment and scenario analysis*.

Fraunhofer ISE. (2015). *What will the energy transformation cost ? - Pathways for transforming the German energy system by 2050*.

GEA, IIASA. (2012). *Global Energy Assessment*.

Greenpeace. (2015). *Energy [R]evolution*.

Hache, E., & Palle, A. (2018). Intégration des énergies renouvelables variables dans le système électrique : analyse bibliométrique et enquêtes auprès des acteurs, 18.

Heating and air conditioning in cars: how much petrol do they consume? | Endesa Clientes. (s. d.). Consulté 29 octobre 2018, à l'adresse https://www.endesaclientes.com/blog/heating-air-conditioning-car

Heating and Car Mileage. (2009, novembre 18). Consulté 29 octobre 2018, à l'adresse https://empiricisms.wordpress.com/2009/11/17/heating-and-car-mileage/

IIASA. (2012). Energy Pathways for Sustainable Development. In *Global Energy Assessment Towards a Sustainable Future*.

J. Allen, & M. Browne. (2010). *Considering the relationship between freight transport and urban form* (p. 78). University of Westminster.

Keramidas, K., Kitous, A., Schmitz, A., European Commission, & Joint Research Centre. (2017). *POLES-JRC model documentation.*

Krook-Riekkola, A., Berg, C., Ahlgren, E. O., & Söderholm, P. (2017). Challenges in top-down and bottom-up soft-linking: Lessons from linking a Swedish energy system model with a CGE model. *Energy*, *141*, 803-817. https://doi.org/10.1016/j.energy.2017.09.107

Le Gallic, T., Assoumou, E., & Maïzi, N. (2017). Future demand for energy services through a quantitative approach of lifestyles. *Energy*, *141*, 2613-2627. https://doi.org/10.1016/j.energy.2017.07.065

Ministère de l'écologie, du développement durable et de l'énergie. (2015). *Stratégie nationale bas-carbone* (p. 208).

Riahi, K., Dentener, F., Gielen, D., Grubler, A., Jewell, J., Klimont, Z., … Morgan, G. (2012). Energy Pathways for Sustainable Development. In T. B. Johansson, N. Nakicenovic, A. Patwardhan, & L. Gomez-Echeverri (Éd.), *Global Energy Assessment (GEA)* (p. 1205-1306). Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511793677.023

Roy, J., Dowd, A.-M., Muller, A., Pal, S., Prata, N., & Lemmet, S. (2012). Lifestyles, Well-Being and Energy. In T. B. Johansson, N. Nakicenovic, A. Patwardhan, & L. Gomez-Echeverri (Éd.), *Global Energy Assessment (GEA)* (p. 1527-1548). Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511793677.027

RTE. (2017). *Bilan prévisionnel de l'équilibre offre-demande d'électricité en France*.

Samadi, S., Gröne, M.-C., Schneidewind, U., Luhmann, H.-J., Venjakob, J., & Best, B. (2017). Sufficiency in energy scenario studies: Taking the potential benefits of lifestyle changes into account. *Technological Forecasting and Social Change*, *124*, 126-134. https://doi.org/10.1016/j.techfore.2016.09.013

Schweizer, V. J., & Morgan, M. G. (2016). Bounding US electricity demand in 2050. *Technological Forecasting and Social Change*, *105*, 215-223. https://doi.org/10.1016/j.techfore.2015.09.001

SFEN. (2018). *Le nucléaire français dans le système énergétique européen*.

The Shift Project. (2017). *Décarboner la mobilité dans les zones de moyenne densité - Moins de carbone, plus de lien* (p. 118).

The Shift Project. (2018). *Peut-on faire mieux que le tout-voiture électrique en France*.

United Nations, & Statistical Division. (2018). *International recommendations for energy statistics (IRES)*.

van Sluisveld, M. A. E., Martínez, S. H., Daioglou, V., & van Vuuren, D. P. (2016). Exploring the implications of lifestyle change in 2 °C mitigation scenarios using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, *102*, 309-319. https://doi.org/10.1016/j.techfore.2015.08.013

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The Shift Project

The Shift Project, a non-profit organization, is a French think-tank dedicated to informing and influencing the debate on energy transition in Europe. The Shift Project is supported by European companies that want to make the energy transition their strategic priority & by French public funding.

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Long-term evolution of the power system supply-side in energy transition scenarios

Technical file #6 – Draft version

Information and recommendations for scenario producers

This document is part of a set of 12 technical files. These files have been produced by *The Shift Project* after one year and a half of research and experts consultations on the different aspects of energy transition and the future studies around these aspects.

Our project, "Power Systems 2050 – Guidelines for design," started in January 2018, with the participation of 10 experts who defined the key subjects which according to them have to be collectively tackled by future studies about the power transition. *The Shift Project* then investigated each of these subjects, consulting in total 40 experts, organizing 4 workshops, and reviewing a large bibliography, including a dozen of future studies about power (and energy) transition at different geographical scales.

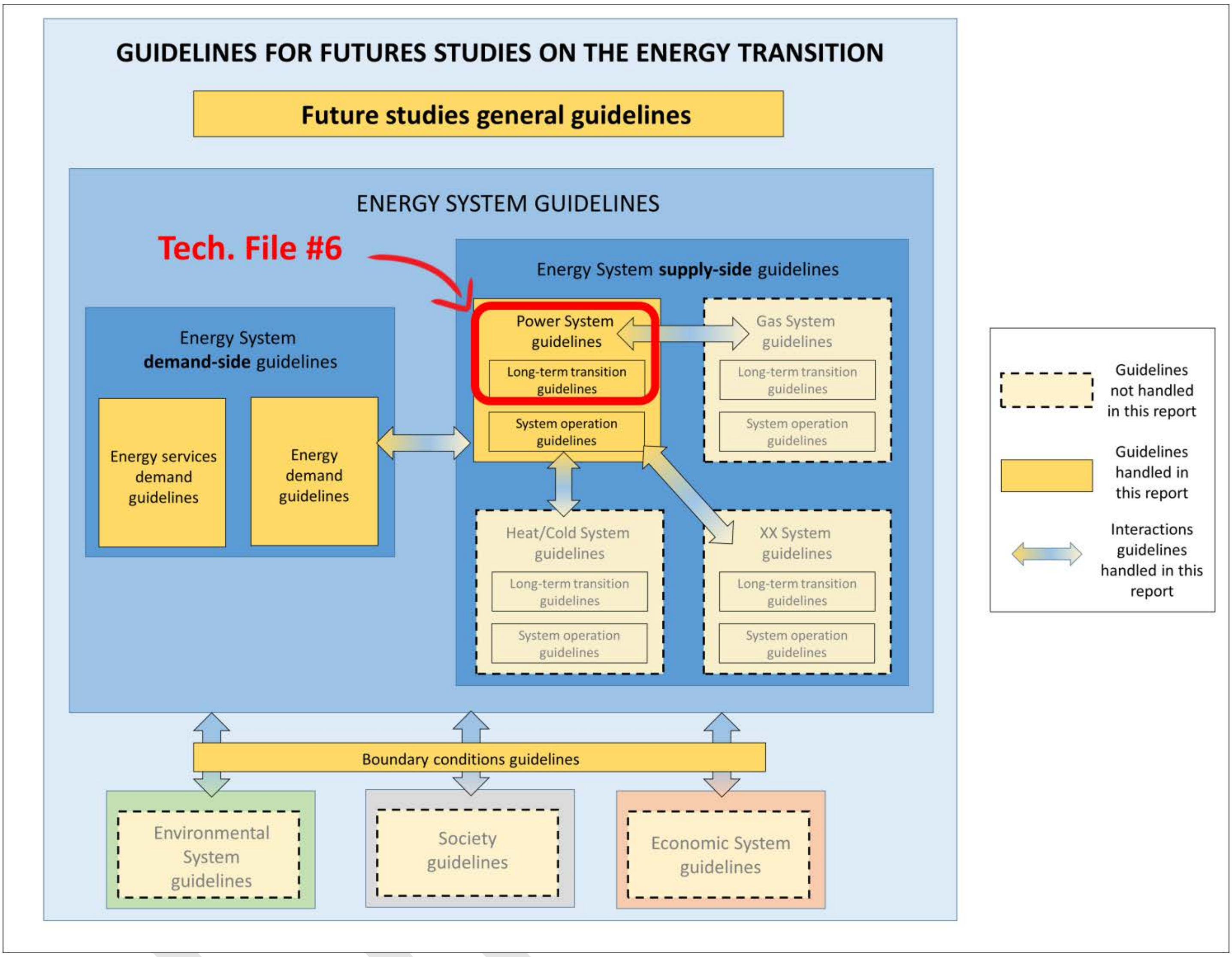
The goal of this project is to produce a set of guidelines addressed to scenario producers. These guidelines seek to **foster transparency and consistency *within* future studies** and to **develop a common language *across* studies**. By defining a number of important items which are key to deal with in future studies, we actually propose a study template which enables a better understanding of the location of each proposed scenario on the tree of possible transitions. Once again, the objective is not to *rank* studies, or scenarios, but rather to *compare* them to get a better collective overview of the different aspects of the transition (what are the differences between studies in terms of driving questions, hypotheses, models, methodology, results?).

Several aspects of the energy transition are handled in these technical files. However, **on the energy supply-side only the power system has been studied**. The main reason for this choice is that we had to start from somewhere with limited resources, and the power system seemed to be a key system to study in the energy transition context, towards a low-carbon economy, as shown by the growing number of future studies focusing on this system. However, the guidelines we propose could be completed by analyzes on the other energy supply-side systems (the gas system, oil system, heat system and so on).

Each technical file tackles several aspects of future studies for the power (and energy) transition. Here is the complete list of the technical files produced during the project:

#	Technical file title
1	Future studies on the energy transition
2	Energy transition models
3	Boundary conditions for energy transition scenarios
4	Long-term evolution of energy consumption in energy transition scenarios
5	Lifestyles and consumption behaviors in energy transition scenarios
6	**Long-term evolution of the power system supply-side in energy transition scenarios**
7	Power system operation in energy transition scenarios
8	Impact assessment in energy transition scenarios
9	Transition desirability in energy transition scenarios
10	Environmental assessment of energy transition scenarios
11	Economic evaluation of energy transition scenarios
12	Employment assessment of energy transition scenarios

Altogether, these files cover the fields described on the following map of the guidelines for future studies on the energy transition. The document you are reading covers the red-circled topics.



In addition to these technical files, **three complementary notes** have been produced as specific focuses on the following aspects: **material criticality** in energy transitions (in French, to be translated and added to technical file #10), levelized cost of electricity (**LCOE**) in energy transition future studies (in French) and **discount rate** in energy transition future studies (in French).

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Table of content

Reading keys

Explanation box, containing key information for a better overall understanding of the subjects.

Recommendations to scenario producers:

These boxes contain the recommendations for scenario producers.

The word "should" means that scenario producers, if they are to follow the guidelines, must substantiate the corresponding point. The words "may" or "might" relates to suggestions, ideas to help the scenario producer respond to the point.

Questions in italic are examples of questions scenario producers might ask to substantiate the points. They are here in an illustration purpose.

Phrases in italic relate to words which are being defined and will be subsequently used in the framework.

Phrases which are highlighted in yellow refer to other technical documents of this series.

I. The power system and its architecture

A. The power system is highly complex and intricated in our daily lives

(Véronique Beillan, Caroline Bono, Sophie Bouly De Lesdain, & Fabien Bricault, 2018) describes how a PS is composed and proposes an overview of how it works. Here are the main points which are developed to better understand PSs.

The PS is probably the greatest industrial system in the world. It must be available 24/7, immediately, and must remain invisible for most consumers. The PS could be described through a multi-layer structure:

- A physical network which follows the rules of physics
- Instant balance between produced energy flows and energy consumption must be kept at all times
- A variety of actors act on the PS following the market rules
- The whole system requires an information technologies layer to properly operate

1. Consumption of electricity reflects a country's activity

Since the beginning of electricity use, the volume of electric energy which is consumed annually grows continuously. Depending on the evolution of other energy carriers (oil, natural gas, etc, see boundary conditions section) and on economic conditions, this growth has been fluctuating.

When speaking about electricity consumption, Whatt-hours (Wh) are often used; for large, national PSs, Twh/yr are used; for electricity bills, kWh are used.

But this is only one aspect of electricity consumption: consumption is dynamical, it evolves permanently. It directly reflects our own activities, and even the activity of a whole country.

It ranges from lighting in dwellings to ovens, electric radiators, washing machines, dryers, vacuum cleaners and so on. Smaller consumptions like mobile phone charging are also counted in.

In addition to these residential uses, tertiary and industrial activity is taken into account, including fabrication processes, steel production, and goods transportation.

Consumption permanently evolves, following a time pattern which is driven by our lifestyles:

- The **night break**: it is the moment when global activity (both industrial and residential) is the weakest, so electric consumption is the weakest too.
- The **morning load rise**: it the moment when a country "wakes up". Inhabitants actually wake up, public transportations start operating, people arrive at their workplaces and economic activity starts; heating systems, computers, lighting, are turned on.
- Then a consumption decrease is observed from noon (breakfast) until a minimum consumption point called **the afternoon break**.
- The end of workday corresponds to another rise in electricity demand. People stop working, go back home, may do the groceries and prepare dinner. At this time, transportation is greatly used (as in the morning), shops, supermarkets are much visited; cooking devices, TV sets, lighting (for shops, public places and dwellings) are turned on. All these activities and uses correspond to the **evening peak**, around 7pm.
- Activity decreases for the night and correspondingly demand strongly decreases. During the evening and the night, little consumption peaks corresponding to the automated start of specific equipment such as electric water heaters can be observed, following tariff signals.

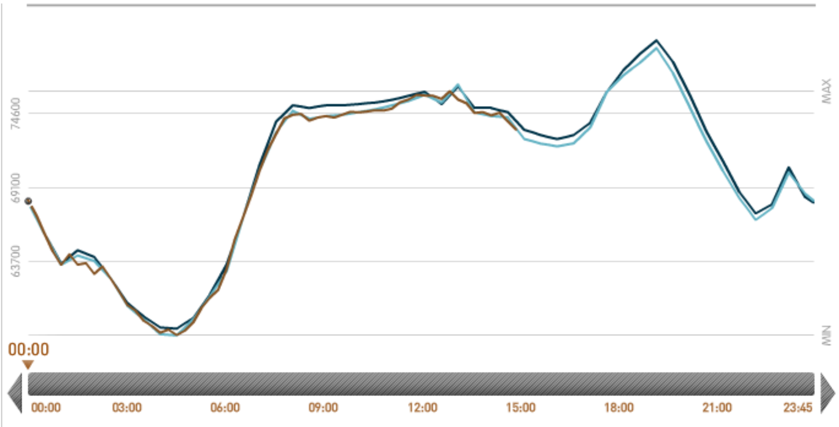


Figure 1: Source éCO2mix, RTE

This type of consumption curves (called load curves) finely reflects a country's activity. As a consequence, the following characteristics can be observed on time scales larger than the day:

- Workdays follow each other, being very similar to each other
- Weekend days are different than weekdays
- Public holidays and vacation periods have specific characteristics
- Winter demand does not have the same shape as summer demand: in summer, longer days require less lighting or heating, etc.

Depending on the country, electric space heating can represent a large share of total heating. The greater this share, the more electricity demand depends on outside temperature. A sensitivity of demand to temperature is observed. This is particularly true in France for example, but other EU countries have a lower sensitivity. Some countries even display the opposite pattern, with a summer peak due to massive air cooling during hot days.

2. A wide variety of generation technologies in two categories: those producing alternative current (AC) and those producing direct current (DC)

Electricity production is a matter of energy conversion, from a primary energy (coal, uranium, gas, wind, sun rays...) to electric energy.

Numerous processes exist, but they do not have the same efficiency nor the same cost, which is important when it comes to large-scale electricity production.

Primary energies which are used to produce electricity are the following:

- Mechanical energy (the most used primary energy to produce electricity, through the work of an alternator)
- Photovoltaic energy (PV), which is booming
- Thermoelectric energy
- Electrochemical energy (used in batteries and power cells)

Electrical current can be produced under a continuous (Direct Current, DC) form or an alternative form (Alternative Current, AC).

Two types of power production units can be distinguished:

- Those which directly produce alternative current. The current is directly injected on the grid through an inverter. The following technologies belong to this category: thermal power plants (using coal, natural gas, oil, uranium to produce heat), hydropower, tide power, concentrated solar power (CSP), geothermic heat...
- Those whose production must pass through a power electronics device (a converter) to be injected on the grid. Most of the "new" renewable plants, called Variable Renewable Energy Sources (VRES) belong

to this category: wind turbines, photovoltaic panels (PV), wave energy technologies, marine current technologies…

3. The grid is the infrastructure for transporting energy from production points to end-consumers

The grid is the physical link between production and the millions of final consumers, would they be individuals, industries or state agents. The grid is composed of numerous technical equipment. Its structure is highly complex.

PS are characterized by several physical values:

- Voltage is expressed in Volt (V). It is similar to the pressure, in a water pipe system.
- The current is expressed in Ampere (A). It is similar to the flow of water, in a water pipe-system
- Power is expressed in Watt (W). It is equal to voltage x current
- Energy is expressed in Watt-hour (Wh). It is equal to power x time
- Frequency is expressed in Hertz (Hz). This value is useful only for alternative current. It represent the speed at which current and voltage waves beat.

These values can be computed everywhere in the PS thanks to well-known physical laws and the fine knowledge of the system components.

In order to connect large production stations to end consumers, the grid is structured in several layers. Those layers correspond to different voltage levels. They have complementary functions.

- Transmission network is responsible for allocating the energy to the different regions. It is the "highway" network of electricity. Large power plants are connected to the transport network. It is also responsible for exchanging the electricity between countries, through interconnexions.
- Distribution network is responsible for bringing the energy from the transmission network to end consumers (industries, companies, households). This is the "small road" network of electricity. Smaller production plants are connected to the distribution network.
- Transborder interconnexions are physical links between PS of different countries. They enable the exchange of energy between them and hence they are support for economical exchanges.

a. Transmission grid

The transmission grid has a structure which is designed to ensure a sufficient security of supply by finely interconnecting regions so has to communalize emergency capacities.

Transmission transformers are the nodes of the transmission grid. They have several functions:

- Transforming electricity from a given voltage level to another, within the transmission voltage levels.
- Allocating electricity thanks to bar sets, and disconnectors (FR sectionneurs)
- Controlling and protecting the PS (control system, sensors, circuit-breakers (FR disjoncteurs))

High-voltage lines are the links between the nodes. Electricity travels through them.

They are mostly open-air lines. Air ensures the isolation between the line and the ground. Lines are produced in conductive material; they have a low resistance but still get heated by the electric current they transmit. As every metal which warms up, they get longer and get closer to the ground. In order to avoid any electrical contact with the ground, the amount of current (intensity) should not be too high.

b. Distribution grid

Source transformers are the nodes linking the transmission grid to the distribution grid. They are in charge of lowering the voltage for the distribution grid. They also participate in the control and protection of the PS.

The structure of the distribution grid is designed to distribute electricity to end-consumers (tree-shaped), with some actuators enabling a certain degree of control over the topography of the grid.

B. The architecture of the PS

1. The larger a PS, the cheaper and the more secure

Historically speaking, PSs used to be located around "sectors", that is, groups of companies and housings which consume electricity. Gathering the different groups into larger electrical regions and further into national electrical regions was soon found economically interesting. This enlargement was further extended to continental regions, e.g. with the installation of high voltage interconnexions between European countries (Véronique Beillan et al., 2018).

There are three reasons why larger PSs are more efficient:

- Economies of scale for production units can be obtained when a large group of consumers is gathered, as production units can be larger.
- Linking the production capacities enables a better reaction to contingencies on production or consumption with the same total capacity.
- The aggregation effect. The linking of production (or consumption) units through a meshed grid leads to an aggregated production (or respectively consumption) whose random fluctuations are statistically reduced (that is, their sum is rarely zero nor the maximal sum). In other words, a wind farm production is much more variable than the aggregate production of all the wind farms of a country; demand from one town is much more variable than the aggregate demand of a country. This effect is illustrated by data measured for a week in France from onshore wind (see Figure 2): at the farm level, variability is high; at the aggregated regional level, variability is lower, and at the national level it is even lower. Also, several different production technologies may complement each other (hydropower stations and thermal stations have different characteristics which are best used in complementarity). These effects enable to benefit from the complementarities between load curves and between production capacities.

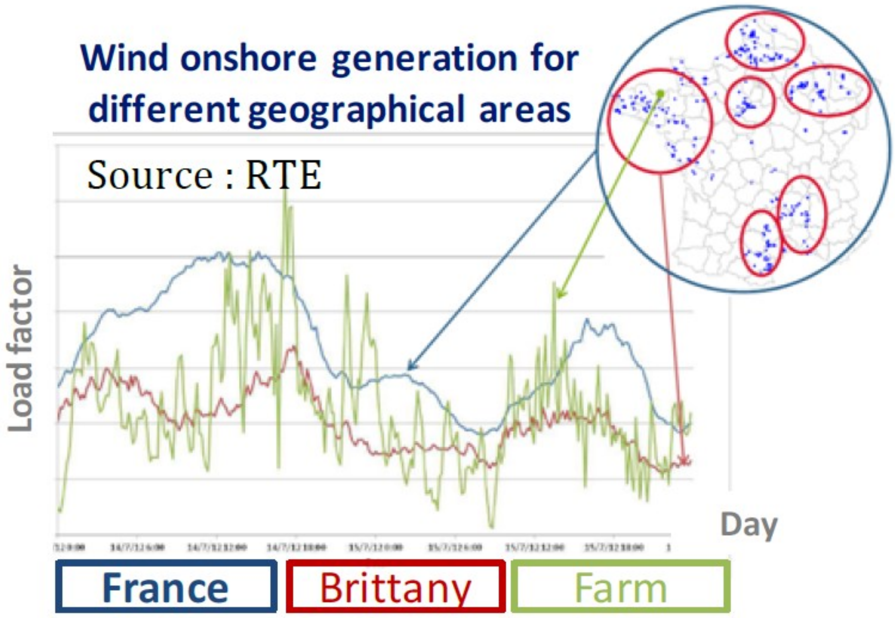


Figure 2: onshore wind generation for different geographical areas in France (EDF, 2015).

Beyond its size, the PS can theoretically have different physical architectures, from highly centralized (which is currently the case in European countries) to highly decentralized.

2. The scale at which the PS is driven greatly determines its structure

Several authors link the physical architecture of the PS to the decision levels which drive its evolution (Foxon, 2013; France Stratégie, 2017; Véronique Beillan et al., 2018).

Indeed the PS can be driven by a variety of scales:

- It can be driven by local decisions. For example, individuals can decide to be power producers through PV; neighborhood dwellers can be involved in an eco-district project with local and national companies, or they can invest in wind power through local crowdfundings; conurbations can define the evolution of their power system through local energy plans.
- Regions can also define power system evolutions (such a trend is re-emerging in Germany (France Stratégie, 2017)).
- Decisions can be taken at a national or supra-national level (as evolution strategies for EU interconnections (ENTSO-E, 2015)).

(RTE, 2017) observes a trend in France towards PV self-consumption by individual households and shows this trend has potential effects on economic flows between agents (individuals, electricity providers, system operators (TSOs and DSOs), the State and territories). Hence aspects of the PS architecture are driven by individual decisions, the remaining aspects being driven nationally.

(ADEME, 2014) points out that local resources in terms of heat, biomass, renewables as well as local needs (depending on the local climate) should be taken into account for a better energy system design. Methodologically speaking, in this study the local thinking is performed at the energy system level, whereas the PS architecture remains centralized at a national level, with more individual self-consumption though. This is also the approach followed by (ADEME, 2015). Here again, some aspects of the architecture of the PS are driven by individual decisions, the remaining aspects being driven nationally. However, no clear overview of the PS architecture is proposed in those studies.

(Association négaWatt, 2014) notes the limitations of self-consumption depending on the type of urban fabric: in dense urban areas, PV self-consumption is not viable because the PV surface per inhabitant is too low. On the contrary, in rural areas, too much would be produced per inhabitant, but distribution network could not handle this production except if heavy investments are done to reinforce it. Hence this scenario keeps a centralized approach for the PS, driven by national decisions.

(Foxon, 2013) argues that the type of actor driving the PS evolution is the key to understand its emerging architecture. Their pathways are articulated around three different types of actors: the central government, market actors, and civil society. In each pathway, one of these actors clearly dominates the debates and drives the PS evolution. Because these actors have different interests and views about the energy system, the resulting PS architectures are different.

- The government logic is to directly co-ordinate the energy system in order to reach policy goals such as being a global leader for some technologies enabling future technology transfers and benefits to UK industry. The top-down management of the transition leads to a highly centralized PS;
- the market logic is to let market actors interact freely within a high-level policy framework (such as a carbon tax, or an emissions trading scheme). Under industry lobbying, the UK government provides support for large-scale low carbon demonstration and commercialization (CCS, offshore wind), also leading to a highly centralized PS (coal and gas with CCS, nuclear, offshore wind);
- the civil society logic is that local actors take a leading role in the decisions about the energy system in order to meet the needs of local citizens. Partnerships between local authorities, housing associations and energy companies lead to energy efficiency of existing building stock, local district heating systems in urban areas, more local investments, domestic and non-domestic distributed generation options. Large industries keep on focusing on nuclear and gas and coal with CCS. This decision patterns leads to a partly decentralized system, backed by centralized elements.

3. Highly centralized, highly decentralized and mixed architectures

(France Stratégie, 2017) investigates the possible PS architectures by imagining three different extreme architectures: totally centralized, totally decentralized, and mixed.

- The totally centralized PS is very similar to the one existing in France. It is based on a transmission and distribution network ensuring the proper supply demand balance without storage technologies, and enables equity between all the consumers connected to the network through a unique national price of electricity. This type of PS can host large shares of VRES if it keeps back-up plants such as new nuclear power or gas and coal with CCS.
- The totally decentralized system is composed of autonomous PSs ruled by cities, neighborhoods or citizens' organizations. It is based on small-scale renewables and inter-season storage technologies and requires some form of solidarity within territories. In this system, equity is difficult to ensure across territories. Consumers need to adapt their demand to variable production, with the help of microgrid information systems and through significant behavior changes.
- The mixed PS is based on a decentralized PS backed by a centralized PS to ensure a high security of supply and transfers between microgrids. Its drawback is the high requirement in investments in order to develop and maintain both systems.

To the best of our knowledge, no future study proposes a totally decentralized PS.

The concept of PS architecture is particularly important to consider as it drives issues of capacity and flexibility sharing between territories as well as the amount of investment required to implement the architecture.

4. Two architectural dimensions: physical and functional

We can distinguish two aspects of the PS architecture: its physical architecture and its functional architecture.

The physical architecture refers to the different pieces of equipment, plants, elements of grids, and their precise location in space and physical links between each of them. Physical architecture can be much centralized with a few large-scale generation plants only (RES or not) and electricity going one way to consumption spots. On the contrary, it can be much decentralized with numerous small-scale generation plants (RES or not) and electricity flowing both ways in the grid.

The functional architecture refers to the way information flows to control the PS. This architecture can be centralized with a global control being performed, no matter the physical architecture of the PS. For example, a global control of interconnected micro-grids with local storage capacities could be proposed in a scenario. On the contrary, the functional architecture can be decentralized, decisions about how to control the PS being taken at a small scale with decentralized intelligence. A decentralized functional architecture could happen around large-scale generation plants, or around micro-grids within a decentralized physical architecture.

Recommendations for scenario producers

Scenarios should include considerations on the PS architecture in their storylines or results. In doing so, the following aspects may be developed:

- Type of physical architecture of the PS: is the PS architecture centralized, decentralized, or mixed? What are the decentralized components of the architecture?
- Type of functional architecture of the PS: Is the PS centrally controlled? Are some elements of the PS partly autonomous from other parts of the PS?
- Actors driving the transition of the PS architecture, and their reasons to drive it this way
- For new types of architectures: analyses of PS security of supply, costs assessments, energy inequities…

II. The evolution of the power system's supply-side in scenarios

A. The drivers of the evolution of the PS supply-side

Scenarios use different approaches to model the evolution of the power-supply side system over the scenario timeframe.

They usually use a one-year time resolution to model the decisions around this evolution, and/or to model the corresponding evolution, more rarely five-year time resolution.

Decisions are made about the evolution of the power capacity, the evolution of the power generation portfolio, the evolution of the grid, the evolution of storage and the evolution of demand flexibility.

Based on the scenarios we studied, we could distinguish two different methodological axes discriminating studies. The first axis is the way time is integrated into decision-making in the model. The second axis is about the specific rules followed in the model when making decisions about the evolution of the PS supply-side.

1. Decisions about the PS supply-side evolution are differently grounded in time in different future studies.

In the different future studies we reviewed, we could distinguish two main different approaches regarding how decision-making relates to time: the time-based approach and the intertemporal approach.

In the **time-based approach**, time is simulated through time steps. At each time step, decisions are made about the power supply-side system, making it evolve (see Figure 3). Decisions are based on what happened at the previous time steps. Models such as POLES (Keramidas, Kitous, Schmitz, European Commission, & Joint Research Centre, 2017), used in (DGEC/CGDD/ADEME, 2015), or the WEM (International Energy Agency, 2018), used in (OECD/IEA, 2017) have this approach.

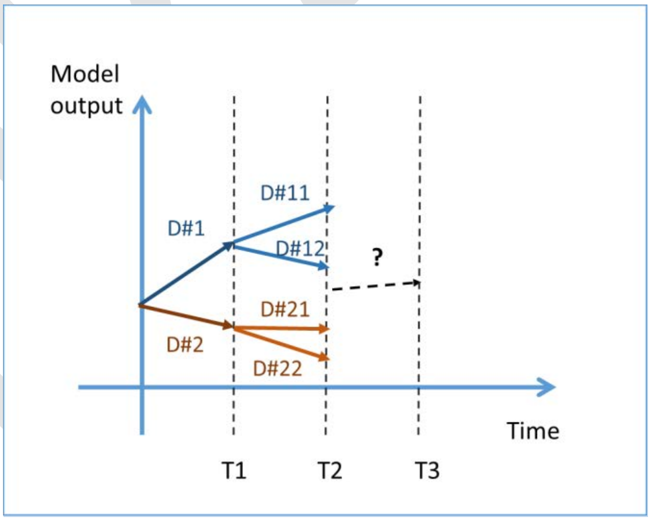


Figure 3: In the time-based approach, at each time step decisions are made by the model to drive the power supply-side system towards a direction. In this diagram, the possible decisions are represented by arrows and are numbered by D#xx. Of course, over the course of a simulation only one path is selected.

In the **intertemporal approach**, decisions are made about the power supply-side system based on a perfect knowledge of all the events happening during the scenario timeframe. In this approach, time is not simulated per se. Instead, some optimization rules are applied over the whole trajectory within the time frame. Some models' documentations talk about "perfect foresight." The intertemporal aspect is more accurate: decisions are made on the total trajectory rather than at "time steps". Hence it is not useful to talk about perfect foresight, because it implies that time-steps are sequentially simulated and that decisions are made at each of them, which is not the case (see Figure 4).

However, some constraints linked to time are represented in the effects of the decisions: power plants and other power installations are tracked and have a lifetime; some constraints on the maximal amount of installations that can happen in one year can also be applied. In other words some inertia can be implemented in the model, constraining the intertemporal decision of the model to some trajectories and excluding the trajectories which do not respect the inertia constraints.

Most of the studies use this approach to drive the PS supply-side. This approach could be called a trajectory designer approach. It may seem less realistic than the time-based approach, but actually the driving questions to which the scenario producers want to answer may justify such an approach. Basically, the goal of future studies is to inform possible pathways and their various implications beforehand, so it may come as natural to take the comfort of globally envisioning the transition to make it more coherent and smoother, sometimes at the expense of understanding and concretely explaining why one decision was made at a given point in time in a scenario and not in another one.

Figure 4: In the intertemporal approach, decisions are made by the model about whole trajectories, as opposed to decisions at each time step.

2. Future studies use different rules to drive the power system supply-side evolution.

We distinguished three different rules driving the power system supply-side in the future studies we reviewed: the cost-optimization rule, the portfolio rule and the preference rule.

a. Cost-optimization rule: the PS supply-side is driven by costs considerations

The **cost-optimization rule** drives the power mix by adding up costs involved along a transition pathway, usually under the form of a total system cost with a social discount rate (see section on economic evaluation) and applying a minimization function to it in order to find the least-cost pathway.

Cost-optimization models are used to apply this rule. These models always use the intertemporal approach, as their goal is to make decisions over whole trajectories (find the least-cost one).

Cost-optimization models are most often working on the PS supply-side only. Hence they require an exogenous power demand trajectory. This is the case for Artelys Crystal (ARTELYS / European Commission, 2017) used in some ADEME studies (ADEME / Artelys, 2015; ADEME / Artelys, 2018) and in (Agora Energiewende, IDDRI, 2018).

The power system module of PRIMES model (E3MLab, 2017) is also a cost optimization model requiring an exogenous power demand trajectory. However, this module is connected to an energy demand module[1] through electricity prices obtained over the trajectory to satisfy electricity producers. Prices affect the demand trajectory

[1] Also see the consumption section.

through different consumption decisions from individuals and companies, and the new trajectory is injected back in the power system module, and so on until this process converges to a trajectory satisfying electricity consumers and electricity producers.

Concretely in these supply-side models, mathematical tools such as Levelized Cost of Electricity (LCOE, called i-LCOE in the economic evaluation section) are used to compare the different competing technologies and decide which mix will be implemented.

Some constraints apply to these minimization choices based on LCOE, usually constraints of minimal security of supply, or similar proxies, for the overall PS. Some other constraints are included in the costs, such as a carbon price.

By taking into account these constraints, the power mix ends up to gather several different technologies rather than the most economic one based on pure-LCOE decisions. If decisions were taken only considering the LCOE of technologies, then the technology with the lowest LCOE would systematically be selected, and the mix would end up with this only technology. This is due to the fact that LCOE does not inform about the future incomes from power sales. In reality, if only one type of technology were installed in the power mix, security of supply would decrease because peak load would not be satisfied, or because fast reserves (FCR, see section on PS operation) would not be large enough in case of event, or because other anciliary services would not be provided.

Models incorporate these constraints by equations checking the proper operation of the power system on an hour by hour basis. This check can be performed with more or less complexity, taking into account several years of weather, simulating weather chronicles; in these checks the weather affects power generation (especially wind turbines and solar panels), but can also affect power demand; also, reserves can be simulated (see below).

A few models optimize conjointly the PS demand-side and supply-side. This is the case of REMod-D-TRANS model used by (Fraunhofer ISE, 2015). This model cannot use linear optimization methods hence instead of using LCOEs it explores a great number of different energy systems and compares their total system costs (see section on economic evaluation) in order to select the one with the lowest cost, without being sure it is the absolute minimum cost.

Note that the cost-optimization rule is sometimes considered by economists as the emerging behavior from "perfect markets". Hence some of the studies using this rule might use narratives about entrepreneurs making decisions instead of a benevolent planner following an optimization rule.

Such studies depicts decisions as if they were made by investors and entrepreneurs in the electricity domain. Indeed, investors are simulated through a "cost of capital" by which they are remunerated for their investing their money in power supply-side systems. Entrepreneurs make decisions to launch projects in such or such power industry taking into the costs they will face (including capital costs) and their expected electricity sales, which can be approximated by LCOE. For example, PRIMES considers its power supply module models "stylized companies aiming at minimizing costs" with a "perfect foresight". The Bilan Prévisionnel 2017, without being clear about the rule it follows, also claims to model investors and entrepreneurs, and distinguishes them for each power generating technology through different remuneration rates depending on the associated risks to invest in this technology (RTE, 2017).

b. Portfolio rule: the PS supply-side is driven by traditional good practices to design centralized PS

Portfolio rule builds up the power mix using "rules of thumb" to decide which technologies to add in the existing mix. The goal of these rules is to get a secure system favoring a variety of technologies without necessarily being the most cost-optimal mix of technologies.

POLES model applies such a rule: it considers different blocks of power production needs depending on the duration over which they happen during the year[2]. For each block and each year, if generation capacity is missing,

[2] Similar to the traditional distinction between base load, semi-base load and peak load but with mode load categories

technologies competes on cost considerations to fill the lack, through a technology portfolio selection process[3]. This process results in a portfolio of technologies within each block of production needs (Keramidas et al., 2017). The WEM proceeds in a much similar way[4] but selects the technologies based on a cost indicator which includes information about the flexibility and ability to provide power at times of high demand[5] (International Energy Agency, 2018). Typically, grid evolution due to the growing demand and due to the selected technologies is considered as a by-product of the mix: grid costs are not considered in the selection process for building the mix.

This rule, as it is based on filling up a gap between demand and already built generation capacity, is always applied in a time-based decision approach: at each time step, the gap is measured considering the capacity which was built or which reached the end of its life in the previous time steps, leading to the decisions. Hence this rule easily fits in econometric models[6] such as POLES and WEM, which cover larger geographical areas (EU, or the world), but which are less technology-rich on the demand-side, than models using the cost-optimization rule. The portfolio rule is based on "traditional" good practices for designing a centralized PS supply-side, which have been efficient to ensure security of supply (such practices are described and discussed in (IRENA, 2017)). Hence the amount of calculation required to apply this rule is lower than a full cost-optimization with security of supply constraints. This is why this rule is more adapted for larger geographical scopes.

Here again, note that this rule could be considered as simulating the behaviors of investors and entrepreneurs.

c. Preference rule: the PS supply-side is driven by an overall storyline

Preference rule builds up the power mix based on a selected storyline which sets overall preferences for driving the power mix. For example, négaWatt studies use a sobriety / efficiency / renewable energy preference rule to drive the energy system and the power system (Association négaWatt, 2014; Association négaWatt, 2017).

Some transition scenarios for UK have been designed imagining dominant actors would govern the power system evolution (Barnacle, Robertson, Galloway, Barton, & Ault, 2013; Barton et al., 2018; Boston, 2013; Foxon, 2013; Hammond, Howard, & Jones, 2013; Hammond & Pearson, 2013): in the Market Rules pathway, the energy system is governed by liberalized and electricity markets as is currently the case; in the Central Co-ordination pathway, the energy system is governed by a central government agency; in the Thousand Flowers pathway, the energy system is governed by civil society. A panel of stakeholders have been invited to directly propose mix evolutions that would fit those different narratives. Finally, a power system model has been used to adjust the obtained power mixes by adding "back-up" capacity, that is, highly flexible and dispatchable power plants.

The Roadmap proposed by ECF explores the conditions to reach pre-defined power mixes. As such, the study sets up preferences towards a few power mixes (deeply decarbonized ones) by forcing the share of energy produced by such or such technology in 2050. The model used then determines the cost-optimal capacity mix which is able to produce this energy (ECF, 2010).

This rule is partly manually applied, partly applied through computational models. It is probably more applicable in intertemporal approaches, as the preferences usually apply to the whole trajectory rather than change at each time steps.

Recommendations to scenario producers

Scenario producers should describe the rule they use to drive the evolution of the PS supply-side in their study. They should explain why such a rule was selected with regard to their driving question(s) and study strategy.

For each rule they should be transparent about the following aspects:

[3] The more costly the technology, the lower its share in the selected portfolio. Limitations are applied for the participation of each technology in each block. For example, peak production cannot be fully covered by variable renewables. Storage technologies other than pumped hydropower are not considered.
[4] Even though it is not clear in the documentation, the portfolio seems to be selected based on some distribution function (Weibull, or logit) such that technologies with lower cost indicator are more present in the final generation mix. The latest WEM (2018) claims to include power storage technologies without providing any detail about it.
[5] They call this indicator the VALCOE, for Value Adjusted Levelized Cost of Electricity.
[6] These models make decisions through a time-based approach, each time step being influenced by the previous ones, notably through elasticity links between consumption and prices. These elasticity links are econometrically measured and are always relative links: "if price increases by x%, then demand decreases by y%."

For studies using the cost-optimization rule, the following aspects should be reported about:

- the cost perimeter, that is, all the cost elements included in the objective function should be mentioned.
- The macro perimeter (supply-side only or whole PS) of the optimization should be mentioned.
- Elements outside the objective function whose cost could significantly evolve between scenarios of a same study. For example, if demand-side is significantly different between two scenarios whereas the objective function has not included demand-side, the results of the optimizations should not be compared.
- Method used to translate LCOE hypotheses into decisions
- Sensitivity analyses on LCOE, especially changes of LCOE ranking: cost-optimization problems are highly sensitive to cost hypotheses, hence this question should be considered. Not considering it should be substantiated: *why is uncertainty on technology relative costs not considered?*

For studies using the portfolio rule, the following aspects should be reported about:

- The technologies participating in the technology portfolio selection process: *are storage technologies taken into account?*
- The selection process: *how is the portfolio designed? What criteria are used?*
- Grid evolution rules, and their place with regards to the technology portfolio selection process

For studies using the preference rule, the narrative(s) driving the power supply-side evolution should be provided. In other words, the different decisions which explain the evolution should be substantiated.

B. The technical components of the PS supply-side with transparency tables

In every scenario, a set of technologies is available for the construction of the supply-side mix. This list, as well as the characteristics of each technology, differ from one study to another. In an attempt to improve comparability between studies so as to foster a participation in a common effort, we present here five tables that can be used by scenario producers.

NB: As developed later, **these tables are not to be "completed"**. The idea is rather to simply transfer the **already-existing** study information (in the form of a value, or a reference to the paragraph dealing with the given characteristic, etc.) in order to **centralize** them in a transparency effort. Therefore, only a part of columns and boxes may be concerned by a given study, the others remaining empty.

The five tables are divided as follows: two tables of technical characteristics (for production units and storage units), and three tables of economic, environmental and social characteristics. The technical and/or economic characteristics are usually those used in the construction of the scenario supply-side mix. Environmental and social characteristics are more commonly used to measure output impacts, but they may also be an input criterion in the same way as other characteristics (e.g. environmental criteria could be used by a benevolent planner to build the power mix).

We have tried to be exhaustive in the characteristics, but scenario producers may want to complete these tables by adding columns where necessary.

1. Objective of the proposed tables: promote transparency so as to foster a common effort in future studies about the energy transition

Each future study defines a set of technologies that can be used to build the supply-side mix. Once these technologies have been defined, the technical characteristics of these technologies may vary from one scenario to another for different reasons:

- The data sources and assumptions used are numerous. Thus, two different studies may use different values for the same characteristic of the same technology.

- For the same technology, the input characteristics (exogenous data) used to determine the mix are not always the same. Thus, two different studies may use different characteristics for the same technology.
- The level of granularity in the list of technologies available in each study may be different. For example, depending on the studies, it may be possible to define a single PV technology, or to distinguish between ground and roof PV, or not to consider this technology at all.

Therefore, it may be important to **bring some clarity** to these specific aspects. As explained in the general introduction (see corresponding part), the goal of the Power Systems 2050 project is **twofold**: sharing **best practices** so as to give scenario producers the opportunity to benefit from them and proposing tools allowing them to adopt a **common "language"** so as to foster a common effort. The 'transparency tables' proposed here primarily aim at addressing this second aspect: **facilitating inter-study comparison**. Our goal is that scenario producers who wants to participate in this common effort use this tables which could be a shared standard for greater transparency. As developed in the Future studies section, transparency is key to foster a dynamic and lively scenario community and, with it, the health of the energy transition debate.

To this end, the idea is simply that scenario producers report in these tables the information **used in their scenarios**. Thus, for any given study, many boxes and columns will remain empty because they do not use these characteristics. The goal is **not** to fill the tables completely. This is a way of visualizing information, of **understanding which characteristics are useful for a study and which characteristics are not**. Again, this depends on the driving question and the study strategy to answer it (see Future studies file). For this reason, each characteristic may either not be used in a scenario, be an exogenous assumption of a scenario, or be an endogenous result depending on the study. In any case, the information is interesting when trying to use the work of several studies (compare, combine, etc.) so as to obtain new elements of understanding.

More generally, the use of these tables is useful in three ways.

First, **for scenario users**, this makes it easier to access this information because it is gathered in a single section of the study report, and thus allows for more transparency, as transparency is about providing digestible intelligence. This is true both for the **understanding of a single scenario** (we can see which boxes are filled in or not, which characteristics have been subject to in-depth analysis, etc.), and for the **inter-study comparison** of these characteristics which is thus greatly facilitated.

Second, **for the scenario community**, it is a real **gain in transparency**. This makes it easier for the different stakeholders in the community to **access** the data, use it to run other models, learn from new methods, etc. It is an effective way to promote debate, to refine hypotheses, to share good practices, and more generally to reinforce and connect the community. Indeed, as described in Transparency paragraph (see Future study file), transparency is a key element to **foster trust** and therefore **build a fertile ground** for the scenario community. This is considered by researchers as one of the most efficient ways to grasp complexity.

As of today, many studies are largely "model-driven". Indeed, many scenario producers do not have access to in-house modeling capacity, so they have to buy modeling services. They usually use off-the-shelf models which already embed huge amounts of data about the national energy systems, there evolutions and the ways they operate. In these cases, embedded data may be privatized and their access may be restricted or subject to a fee. Scenario producers may not have the right to publish these data even though they are contributing to a public debate. This raises the question of the collective transparency which is required in such an important debate as the one about the energy transition.

Finally, **for scenario producers**, the use of these transparency tables allows to build trust, both towards users of their study, and within the scenario community. This makes it possible to better communicate their messages (see Trustworthiness paragraph in Future study file).

These tables can also provide a basis for scenario producers who wish to ask themselves new questions. For inexperienced script producers, this can be an interesting starting point for inspiration and thus promote the emergence of new future studies. For more experienced producers, it is an opportunity to ask new questions that may lead to additional elements (for example on the impact of climate change on different technologies).

Recommendations for scenario producers:

So as to participate in a common effort within scenario community, scenario producers may use the presented transparency tables. The following sections describe these tables and provide guidelines in the way they may be used.

2. The characteristics described in the tables can evolve over the study timeframe

Most of the characteristics presented in the tables can vary over time and thus during the scenario timeframe, especially due to technical progress. This evolution in technology maturity can be expressed through various characteristics, either exogenously or endogenously. For example, technical progress often appears in cost characteristics. The choice of characteristics that are evolving can be explained.

An often used method to determine a technology characteristics evolution is to apply a **learning rate** to its costs. As described in (Dii, 2012) : "a common (and technology independent) way of estimating cost reductions over long time periods is that of learning curves. This empirically proven approach shows that maturing technologies undergo a rate of cost reductions that depends, in a roughly linear fashion, on how often the installed capacity of the technology doubles. Thus, the worldwide installed capacity of a technology at the beginning of the time horizon under consideration has a major influence on the rate of cost reduction per installed GW."

Learning rates are widely used, as in model PRIMES, (ECF, 2010) or (Greenpeace, 2015). (ECF, 2010) uses for example two types of learning rates: a reduction in cost per doubling of cumulative installed capacity for new technologies, and a yearly improvement for 'established' technologies. The cost reduction is directly applied on the technology CAPEX. The values of these rates are determined through industry participation workshops.

However, as argued in (JRC, 2014), this approach is a common simplification. Cost reductions are indeed the result of more complex processes. They thus recommend to use learning rate with caution. Pursuing price reduction under certain limits could indeed not be feasible in reality. Hence a narrative could be provided to explain how and why the planned cost reduction will occur in the scenario. (ECF, 2010) for example substantiates the CAPEX reduction of some plants by providing values about the improvements of their efficiency.

Recommendations for scenario producers:

A narrative may be provided to justify the chosen characteristics evolution over time. For example, in the case of learning rates, insights about relocation and prices of imports may be discussed.

Do prices decrease due to evolutions in the production places? Do prices include possible tensions about materials/goods?

3. Table of technical characteristics for generation units

In this section, we consider the different technical characteristics of generation units. They are summed up in this table (Figure 5), and developed in the following paragraphs:

	TRL	Unit capacity	Energy yield	Life duration	Dispatchability level	Dispatchability main constraints	Resource predictability	Resource potential
Wind								
PV								
Nuclear								
Gas								
...								

Maximum installation rate	Production profile	Load factor	Availability factor	System storage function	Ancillary services	Impact from climate change

Figure 5: Generation units' technical characteristics table

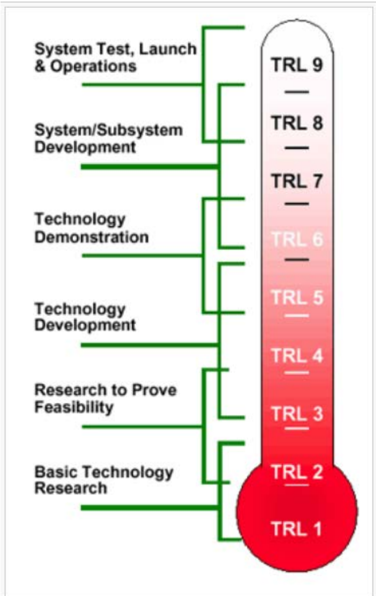
NB: To integrate technologies that modify several characteristics of plants such as CCS, several option can be used:

- describe all the modification that CCS (or other technology) brings in a specific paragraph. E.g.: plant efficiency is reduced by 20% while CO_2 emissions are reduced by 50%, etc.
- each technology using CCS can be a new row in the table (one row for coal and one row for coal+CCS, etc.)

In any case, a specific paragraph about CCS is useful to discuss considerations such as competition about storage space (as with industry), CO_2 transport network and its distance to each generation unit equiped with CCS, abatment cost of avoided ton of CO_2, etc.

d. Technology maturity : a combination of TRL and CRI indicators

The **Technology Readiness Level** scale is a rating system used to evaluate how mature a technology is. The scale starts at level one (basic technology research) up to level nine (system test, launch and operations). As explained in (IEA, 2015): « *TRLs can be used to assess how far a technology is from market, and hence the uncertainties in other evaluation metrics.* »



NASA Technology Readiness Levels

Source: Wikipedia

It can be used for generation unit as well as storage units, as in (Brouwer, van den Broek, Zappa, Turkenburg, & Faaij, 2016) for example. The TRL indicator does not take into account any notion of costs, but it can be linked with other indicators such as the discount rate: higher levels of technology readiness signal indeed lower perceived risks (Engel, Dalton, Anderson, Sivaramakrishnan, & Lansing, 2012) , and thus lower discount rates.

The TRL indicator has been designed to be used in the research and development sector, particularly for **systems not yet commercially available commercialized**. Thus, any large-scale electricity production technology in use today is rated nine (i.e. the maximum) on the TRL scale.

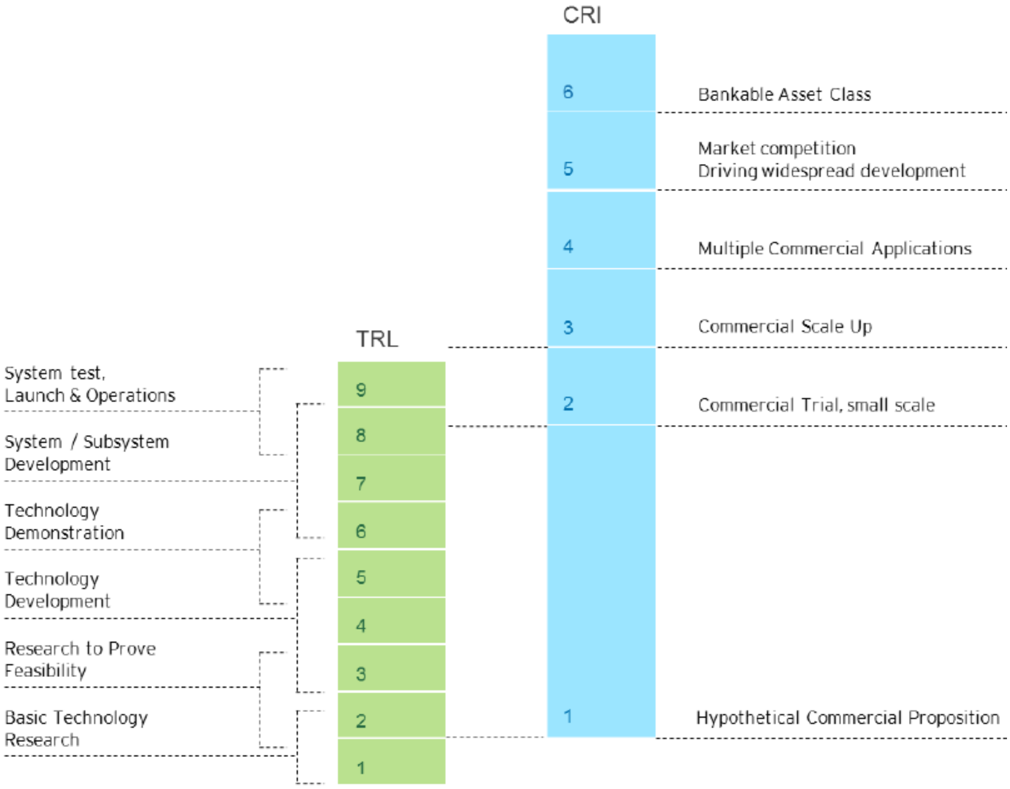
This indicator can be useful in the scenarios when trying to evaluate how mature an emerging technology is. For example, it can help to determine the year of availability of a specific technology in a scenario; and/or be used to eliminate some technologies for a particular scenario. This method has been used in the study (Association négaWatt, 2017): in order to make technologies "realistic choices" (i.e. the technologies will be available soon enough, in sufficient quantities, with reasonable costs and acceptable impacts), only those with a rated TRL above nine have been "significantly used" in the scenario.

The study (ANCRE, 2017) uses the TRL indicator as well: a recommendation of this study is to pursue and orient a significant part of the research towards projects with a 'medium' TRL (i.e., between four and seven).

TRL can be completed with other indicators. (Association négaWatt, 2017) study presents for example Manufacturing Readiness Level (MRL) and the Environmental & Social Readiness Level (ESRL). These indicators enable to address other dimensions of technology maturity. However, these two scales tend to overlap with the TRL scale (i.e., for every given technology TRL level, there is the same corresponding MRL and ESRL level most of the time). Furthermore, the MRL and ESRL scales do not go significantly « higher » than the TRL scale. In the end, it seems they do not really bring valuable further insights to select technologies.

As the TRL indicator does not allow any distinction of already-mature technologies, a more interesting complementary indicator would be the Commercial Readiness Index (CRI). It has been developed by the Australian Renewable Energy Agency (ARENA) for that specific purpose. The CRI indicator takes into account costs and is mainly directed to technologies with a high TRL value. CRI may thus be a good indicator for scenarios, especially for renewable energy technologies:

Figure 1: **TRL and CRI**



Source: (ARENA, 2014)

(IEA-RETD, 2017) explored the use of CRI for **renewable energies** as a **tool helping decision making** when implementing public policies. For example, the study explores and shows how a technology such as solar PV in Germany, with a TRL of 9 in 2003, progressively climbed the CRI scale thanks to several energy policies (see corresponding annex). This study concludes that the CRI can be useful at different levels and lists its limitations as well. These conclusions are presented in corresponding annex.

e. Unit capacity

This column can be used to **explain choices about the capacity of production, or storage units.** *For each technology, is a unitary capacity value set? Is the value changing over time during the scenario? Can different plants of the same type be built with different capacities on the same year, and if so, how is the choice made?*

Moreover, it may also be interesting to specify if the approach toward overall installed capacity is discrete or continuous. *Is it possible to install any given capacity value or does it have to be a sum of individual plant unitary capacities? Is it possible to install "one third of a power plant"?*

As the other characteristics presented here, this one it is not necessarily useful in some studies, but it can be found in others. The unit capacity can be expressed in Watts (kW, MW, GW) but also as in W/m², or W/any relevant functional unit. In this case, it may be useful to provide additional information. For example, in the case of W/m² for solar panel, it can be useful to specify these are m² of ground or m² of panel.

Some studies provide detailed analyses of how other technical characteristics may interact with unit capacity and thus anticipate its evolution over time. As an example, (ADEME, 2015) discusses new types of wind turbines with higher unit capacity with regards to characteristics such as the size of the rotor, the specific surface, etc.

f. Energy yield

The energy yield of a plant is the **ratio between input and output energy**, expressed as a percentage. This parameter is mainly used in the case of fossil fuel plants. It may evolve during a scenario, increasing most of the time as a result of technical progress. Such evolution over time may be linked with cost reductions.

(ECF, 2010) for example indicates the efficiency evolution of new plants in its scenarios between 2010 and 2050: from 58% to 60% for gas plants and from 45% to 50% for coal plants.

g. Life duration

This is a useful parameter to understand the **power generation mix evolution pace**. It may be interesting to specify this indicator: *is it a "technical" lifetime or an "economic" lifetime that is considered? Something else? What definition is used?*

For example, (ECF, 2010) defines the economic lifetime as "the average depreciation life" (e.g., 40 years for a coal-fired power plant, and 30 years for CCGT).

h. Dispatchability level

An important and often used distinction regarding the operability of a plant is whether it is **"dispatchable"** or not. This distinction may be interesting, and some studies such as (ADEME, 2015) use it, as for renewables technologies used in the scenario. Non-dispatchable units can sometimes be called **"variable"** (the term "intermittent" can also be found, but is generally deemed to be more pejorative).

(ECF, 2010) for example defines dispatchability as "the ability of a resource to respond to specific instructions to operate in a given mode at a given point in time with a high degree of reliability". Dispatchability is linked to the presence of an input energy resource which is stored, allowing to modulate the output power of a plant at the appropriate time; as opposed to technologies depending on an energy flow that cannot be stored as such for their production.

Scenario producers could also chose to bring **additional information about the dispatchable/variable nature** of generation units. Indeed, it may happen that some 'variable' technologies can be controlled to a certain extent, typically downwards. Also, some technologies usually described as dispatchable may be subject to unexpected constraints, and therefore, in some ways, may show downward variability. Therefore, this type of distinction could be introduced: dispatchable upwards and/or downwards; variable upwards and/or downwards.

In any case, since there is not exact consensus on these definitions, the best option is that the scenario producer provides its own definition.

Moreover, it may also be possible to specify the **"level of dispatchability"**, and by doing so to avoid choosing between dispatchable or variable. To that extent, a set of specific characteristics can be provided, such as ramp up and ramp down capabilities, minimal or maximal operating points, etc. (see Flexibility paragraphs in Power system operation file for more insights on this topic).

i. Dispatchability main constraints

To complete information about the level of dispatchability of a generation unit, it can be useful to provide information on its main dispatchability constraints to understand under which limits a dispatchable unit is still dispatchable.

One can therefore list:

- **Constraints on the energy stock and/or energy flow**. For example: the dispatchability of hydropower plants remains limited by the level of precipitation and/or the capacity of the reservoir; failures in coal storage silos have in some cases prevented coal power plants from operating properly; the dispatchability of gas power plants in peak conditions can be limited by the maximum flow of the gas network that supplies them, etc.

- **Economic constraints**. One example is the costs to stop and start a plant, which explain why some power producers prefer to pay for electricity production during negative electricity price periods rather than temporarily shutting down the plant.

- **Regulatory constraints**.

- Other constraints related to **plants specificities** can lead to limited electricity production, such as the heat production part for CHP plants, cooling requirements for nuclear power plants, etc.

j. Resource predicatability

Another important element with regard to dispatchability is the **ability to predict plant production**. This depends on how the resource is stable in a day and over the year, and also on the evolution of knowledge and modelling capabilities on this particular resource.

It may also be interesting to provide considerations about the ability to predict any constraints on energy stock or flow.

k. Resource potential

For each type of technology, it is possible to define a maximum resource potential. However, it is important to specify what **the type of potential** is.

On the one hand, **five types of potential can be listed for renewable resources**. They can be expressed either in energy units per year (TWh/year for example) or in power (GW for example). (Greenpeace, 2012) summarizes what the five types of potential are as represented in the box on the right.

Theoretical potential may evolve for some resources if new discoveries are made (e. g. new terrain suitable for hydropower), and according to changes in the environment that provides the renewable resource (e. g. forest degradation, which can no longer produce as much wood each year). However this is not the case for solar irradiation for example. Conversion potential evolves with technical progress, while economic potential evolves according to the costs of exploiting the resource, and according to the price on the markets.

On the other hand, **for non-renewable resources, a distinction is made between reserve and resource**. The resource is the total existing quantity of a given material, while the reserve is the known, technically and economically exploitable quantity of this material. The resource therefore corresponds in a way to the theoretical potential, while the reserve corresponds to the economic potential.

box 8.1: **definition of types of energy resource potential**[77]

Theoretical potential The physical upper limit of the energy available from a certain source. For solar energy, for example, this would be the total solar radiation falling on a particular surface.

Conversion potential This is derived from the annual efficiency of the respective conversion technology. It is therefore not a strictly defined value, since the efficiency of a particular technology depends on technological progress.

Technical potential This takes into account additional restrictions regarding the area that is realistically available for energy generation. Technological, structural and ecological restrictions, as well as legislative requirements, are accounted for.

Economic potential The proportion of the technical potential that can be utilised economically. For biomass, for example, those quantities are included that can be exploited economically in competition with other products and land uses.

Sustainable potential This limits the potential of an energy source based on evaluation of ecological and socio-economic factors.

Source : (Greenpeace, 2012)

Several more or less detailed methods exist to define all these resource potentials, both for renewables and non-renewable sources. It can be a narrative, as in (ECF, 2010) on fossil energy reserves, or a detailed approach for each sector as in (ADEME, 2015)[7], where the potential for each renewable sector is studied with a high geographical granularity and topological and societal constraints. Legislative and economic aspects are also taken into account using several databases.

As there can be a competition between different resources, scenario producers should provide information on the global consistency of their resource assessments. Such a global approach requires to solve extraction conflicts between several resources (such as land use conflicts).

l. Maximal installation rate

In the real world, there are obviously different types of **limits** to the installation pace of different units. However, it is impossible to decide on a single maximum rate value: those limits depend on the hypothesis made in the storyline and therefore vary from one scenario to another. If no maximum installation rate is calculated, then it can be interesting to qualitatively substantiate the observed installation paces in the scenario.

This can be linked to resource potential, as resource quality can decrease when new installations progressively appear at the best locations. Maximum installation rate also depends on the **amount of skilled workforce** in each sector required to meet the human resource requirements in time (see employment data column in Economic characteristics table).

m. Production profile

Production profile is the **hourly production potential** of a generation unit. For a renewable variable units, it depends directly on the resource at the location where the unit is installed: the PV production profile depends on irradiation profile, wind power profile depends on the wind profile, etc. Therefore, production profile varies depending on the location, the day, etc. This enable to introduce the previously mentioned decrease in renewable resource quality as best locations are progressively used.

Production profiles are mainly useful for variable renewable installations. For other types of installations, it is possible to use the "base load / mid-merit / peak load" categorization. It tends to be less and less used as the share of variable renewables increases in the electricity mix, but it can still provide useful information. (ECF, 2010) for example distinguishes "baseload plants" that "operate generally around the clock, at least at part load" and "mid-merit plants" that "are turning up and down, and even on and off, with normal daily fluctuations in demand". They categorize coal-fired power plant as "baseload plants" and gas-fired power plant as "mid-merit plants". This categorization depends on the choices made on the study. In the real world, it changes from one country to another.

n. Load factor

This parameter can be expressed as % or h/year.

For **variable generation technologies**, the load factor is a partly exogenous data. It can be used to calculate the resource conversion potential as load factor value directly depends on the renewable resource. It may also vary during the scenario due to technological progress.

For **dispatchable generation technologies**, the load factor is rather an endogenous variable according to the choices made in the scenario storyline and/or results of the model simulation. It can be linked with choices about the previously presented base load / mid-merit / peak load categorization.

o. Availability factor

Load factor can be linked to availability factor, which indicate what **proportion of the time a given plant may actually be in use** for electricity production. This enable to introduce plant closure planning, and therefore plant

[7] This detailed approach is transparently explained in the study and provides useful methods and information on renewable resource potential.

unavailability due to unforeseen events, maintenance operations, etc. It may be interesting to specify both the average value of this availability factor and its value when the plant is in a peak situation.

p. System storage function

Some generation technologies may have an **additional storage function** besides their production function. This additional function can be either 'system' or 'local' storage:

- A ***system storage function*** allows to store electricity from other production units. This is the case for the great majority of storage systems, which thus enable to provide a storage function 'from the power system point of view'.
- A ***local storage function*** only permits energy storage for the given specific technology. This is the case, for example, for concentrated solar power technology which stores energy under heat form. This type of storage function does not provide any storage capacity for the system as a whole. However, it enables the technology to improve its dispatchability.

Therefore, it is not relevant to specify local storage function here (it can instead be mentioned in columns related to dispatchability). Only system storage function should be specified in this column, and a corresponding row in the storage units technical characteristics table should be added.

NB: In the case of hydropower, it may be interesting to distinguish hydropower alone (no system storage function) from mix pumped hydro storage (PHS) (both system production and storage function) and from pure pumped hydro storage (storage function only). Indeed, resource constraints are different for mix PHS and pure PHS.

q. Ancillary services

Some production units also provide **other types of services from a system perspective**. These are called ancillary services, such as voltage control, rotor angle stability, flexibility function, reserve function, inertia function, etc. Detailed and illustrated explanations about ancillary services can be found in Power system operation file.

r. Impacts from climate change

Climate change we are experiencing has and will have increasing impacts which can affect generation infrastructure in various forms. It may be interesting to develop these elements for each technology, and to specify for example if **adaptation measures** are implemented to reduce exposure to **physical risks**.

E.g.: the increase in frequency and intensity of extreme events as well as the rise in sea level can damage some equipment such as onshore and offshore wind turbines, disturbance of water cycle can impact water resources and therefore hydroelectric potential, increasing temperatures and heat waves can reduce PV panel energy yield and affect cooling capacity for nuclear power plants, etc.

Some effects can already be observed today, such as the decrease in snow stock and therefore of hydroelectric potential. For the other effects that could be negligible in the medium term, several opinions consider that many impacts will no longer be negligible as early as 2040-2050. Therefore, it might be interesting to estimate costs of adapting to these impacts (see Power system inventory in Economic Evaluation file).

NB: There seems to be a lack of information on this subject. Climate models are indeed not able to provide accurate estimates for the 2040-2050 horizon since they are rather designed to assess impact in year 2100.

4. Table of technical characteristics for storage units

Along with the construction of models and scenarios, storage issue is **one of the most studied** in the field of renewable energies integration into electricity networks (Hache & Palle, 2018). Storage units, if deployed on a large scale, indeed make it possible to store electricity when it is in surplus and to restore it when it is needed at the power system level, which is a highly useful service when the power system includes a high share of variable energy sources. Electricity storage is achieved by **transforming electricity into another form of storable energy** and then by transforming it back when needed. There are many possible techniques for that purpose, through three main forms of energy: mechanical, chemical, and thermal.

Here is a list of main electrical storage systems: pumped hydro storage (PHS), thermal energy storage (TES), compressed air energy storage (CAES), small-scale compressed air energy storage (SSCAES), energy storage coupled with natural gas storage (NGS), energy storage using flow batteries (FBES), fuel cells—Hydrogen energy storage (FC–HES), chemical storage, flywheel energy storage (FES), superconducting magnetic energy storage (SMES), energy storage in supercapacitors. (Ibrahim, Ilinca, & Perron, 2008)

The presented **table of technical characteristics for storage units** is composed of the following columns.

	TRL	Type of application	Storage duration	Storage capacity	Power output	Cycling capacity	Efficiency	Storage potential	Operational constraints	Impact from climate change
Pumped hydro storage										
Compressed air energy storage										
...										

Figure 6: Storage units' technical characteristics table

TRL

The Technology Readiness Level indicator applies to both production and storage units. (see paragraph on TRL)

Type of application

In order to understand what type of service the storage unit provides, it may be useful to specify whether it is a large unit at the production level or a small unit at the consumer level that provides a demand flexibility service. It may also be interesting to specify whether the considered unit is stationary or mobile.

Storage duration

This is the main temporal aspect of storage units. Each type of storage system can store energy either on the short-term or on the long-term. For example, several types of periods can be distinguished: intraday, daily (or intra-week), seasonal, etc.

Storage capacity

This is the quantity of available energy in the storage system after charging. This is obviously a key characteristic of storage systems. This information can be completed with mass and volume densities of energy: these represent the maximum amounts of energy accumulated per unit of mass or volume of the storage unit, and demonstrate the importance of mass and volume for certain applications. (Ibrahim et al., 2008)

Power output

This is the speed at which stored energy can be released and thus determines the time needed to extract it. This is another key characteristic depending on the maximum power needed, especially during peak hours.

Cycling capacity

This refers to the number of times the storage unit can release the energy level it was designed for after each recharge, expressed as the maximum number of cycles (one cycle corresponds to one charge and one discharge). This is the main durability indicator for storage system. All storage systems are subject to fatigue or wear by usage. This is usually the principal cause of aging, ahead of thermal degradation (Ibrahim et al., 2008). Therefore life duration is not a relevant indicator to express storage system durability.

Efficiency

This is the ratio between released energy and stored energy. It enable to estimate how much energy is lost when it requires to be stored.

Storage potential

As with for the resource potential deposit for production units, it may be interesting to estimate the storage potential, quantitatively or qualitatively, as well as the main limits that can be identified. (ECF, 2010) for example states that "European hydro plants have unused potential for optimization of their storage potential". The study uses this identified margin in its scenarios and also specifies that « As these systems require mountainous areas this type of storage has some geographical limitations and therefore cannot always be placed at locations where it might be needed most. Innovative concepts on artificial islands in the sea have been launched".

For other types of storage such as batteries, one can also think about limits related metals criticality (see section on environmental assessment).

Operational constraints

Constraints in the storage systems operation mainly come from safety issues (explosions, waste, bursting of a flywheel, etc.) and operational conditions (temperature, pressure, etc.) Considerations about monitoring and control equipment may be added as this equipment can have consequences on both the quality and safety of storage.

Impact from climate change

As for generation technologies, storage technologies are exposed to physical risks due to climate change and adaptation measures can be required.

E.g.: the increase in frequency and intensity of extreme events as well as the rise in sea level can damage some equipment, increased temperatures and heat waves can reduce efficiency and accelerate the degradation of batteries, etc.

Finally, **other more specific characteristics** can be added if the scenario producer considers it useful. It may include insights about self-discharge (which is the portion of the energy that was initially stored and which has dissipated over a given amount of non-use time) or other characteristics that sometimes depend on specific installation parameters such as autonomy or discharge time.

5. Table of economic characteristics

Concerning economic characteristics, other files already address in depth several aspects: see files one economic evaluation, job transition, LCOE and discount rate.

Here are the main characteristics that can be summed up in a table:

	CRI	CAPEX	OPEX	i-LCOE / i-LCOS	WACC	Employment data
Hydro						
Gas						
Batteries						
...						

Figure 7: Economic characteristics table

CRI

CRI indicates the commercial readiness level of a technology and can be a good complementary parameter to the TRL, as described in TRL paragraph.

CAPEX

Capital Expenditure of a technology are all the investments to build the unit, extend its life duration, and spare money (provision) for future expenses as dismantling or waste management. It can include the financing costs of those investments (i.e. capital costs). CAPEX can be expressed as a euros per unit of capacity (e.g., €/kW).

OPEX

Operating Expenditure of a technology comprises all costs required to make the unit run correctly. It includes fixed costs as worker wages and regular maintenance operations and variable costs such as the purchase of fuel and quotas on carbon market for some generation technologies. A narrative about fuel prices evolution can be provided.

Both for CAPEX and OPEX, what is included may be clearly defined by scenario producers since the same terms can sometimes have different meanings depending on the study (e.g., "variables costs"). See Economic Evaluation for more details on CAPEX and OPEX.

i-LCOE / i-LCOS

As described in the note about LCOE, i-LCOE indicator (for "investors LCOE", as opposed to "system LCOE"), indicates the cost of electricity produced for a given technology, for a given year. A similar indicator exists for electricity storage system: the i-LCOS (investors Levelized Cost of Storage) and indicates the cost of stored (and then released) electricity. Some scenarios use this indicators to determine the supply-side mix while other do not. See LCOE file for a detailed analysis of LCOE indicator.

WACC

Weighted Average Cost of Capital is the discount rate allowing to integrate the remuneration expected by financers (i.e., capital costs) in calculations for a specific project. The WACC value can have a significant impact on the profitability of a project, especially for capital-intensive investments (i.e. projects with high CAPEX and low OPEX) like most of decarbonized generation technologies. A justification of the chosen value and its evolution according to the several types of risks taken into account (country risk, delivery and legal risks, etc.) can be provided. See private discount rate paragraph and its explanation box on WACC in Discount rate file for more details.

Employment data

In this column, scenario producers can include information such as employment factors and considerations about the amount of skilled workforce in the given sector. Indeed, meeting the human resource requirements of sectors in rapid expansion requires education and training policies to avoid bottlenecks. See Job transition file for more details.

6. Table of environmental characteristics

Every type of unit interacts with its surrounding environment, in two ways: by extracting resources from it and/or by releasing substances in it. By and large, this participates to several issues that can be either local or global.

Some of these interactions can be easily measured and expressed as physical quantities, while others are more of a diffuse nature and are better expressed qualitatively. For quantitative impact, many data sources present value of resource extracted or substance released by unit of produced (or stored) energy: gCO2eq/kWh, gSO2eq/kWh, etc. (United States Department of Energy, 2015) study provides to that extent tables on GHG emissions, air pollutants, water use, land use and material criticality for different technologies (see corresponding annex).

Here is the environmental characteristics table :

	Material criticality	Land use	Water use and pollution	Climate change	Air pollution	Solid waste	Biosphere
Hydro							
Gas							
Batteries							
…							

Figure 8: Environmental characteristics table

All the following elements are explored more in detail in Environment section. For each element, scenario producers can present qualitative consideration in any case and quantitative values (see corresponding annex).

Material criticality

Metals and other materials are, along with fossil fuels, one of the main stock resources that we use on a large scale on the planet. With increasing exploitation on a global scale, the depletion of several specific metals and materials raises geological criticality questions, as for copper for example.

Land use

Some infrastructure require larger areas than others, which can raise competition issues about land use such as food production.

Water use and pollution

The impact on water is both due to withdrawals and substance releases into watercourses such as hotter water, in the case of thermal power plants, or indirect acidification of watercourses due to substances first emitted into the air. Water withdrawals as with hydroelectricity or the need for cooling water from thermal power plants can cause competition on water resources.

Climate change

Climate change is due to greenhouse gases (GHG) emissions, and especially CO_2 in the case of power system infrastructures. Concerning CO_2 emissions, two main categories can be distinguished :

- High-carbon technologies are those using fossil fuels combustion and have significant emissions occuring during use phases due to combustion in addition of the smaller emission during production/end-of-life phase due to construction work. These generation technologies are, from the most emissive to the least emissive, Coal – Oil – Gas.
- Low-carbon technologies are all the production technologies. Significant emission only occur during production/end-of-life phases due to construction work. Solar PV has the highest value among those technologies. Wind, geothermal and nuclear usually have the lowest values.

Air pollution

It is the main direct cause of death due to the use of electrical system infrastructure. It is mainly due to several substance emitted during combustion such as *particulate matter, sulfur dioxide, nitrogen oxides, carbon monoxide, etc.* Exposure to these pollutants can damage people's cardiovascular, respiratory and nervous systems, increasing the risks of lung cancer, stroke, heart disease, chronic respiratory diseases and lethal respiratory infections. As for GHG emission, coal has the worst impact by unit of produced energy. Unlike GHG emissions, this is not a global issue but rather a local one.

Solid waste

Different types of solid waste, including nuclear waste, can be generated when using power system infrastructures.

Biosphere

More difficult to measure than other characteristics, the impact on the biosphere can be assessed qualitatively. One can think of reservoirs dam construction implying ecosystem damage, aquatic ecosystems perturbation during use phase, and other types of problems if dam breaks; or impacts of floating offshore wind turbine that can be both positive and negative as is marginally kills some species but also encourages biodiversity development by protecting areas; etc.

NB: other categories can be defined. The impacts related to the release of substances can typically be presented in two ways: either by major type of end-point impact (climate change, human health, etc.) or by type of substance emitted. Indeed, the same substance can participate in several end-point impacts, and each end-point impact can be the consequence of the emissions of several substances (see LCA approach).

For example, CO_2 contributes to greenhouse effect and therefore to climate change, but also to acidification of the oceans. Similarly, SO_2 contributes to air pollution, but also to the acidification of water, soil, etc.

7. Table of social characteristics

Finally, in terms of social aspects, only a few columns are presented because most of these aspects are more **related to systems as a whole** than to particular technologies. Three columns are distinguished here, in line with the distinction made in Desirability section:

	Landscape	Safety risks	Other human ecology impacts
Hydro			
Gas			
Batteries			
...			

Figure 9: Social characteristics table

Landscape impact

Some infrastructures modify local landscapes such as overhead lines, wind turbines, etc. It can be a key factor in local acceptance problems. This is linked to the concept of place attachment.

Safety risks

One can think of risk of fire starting, risk of leakage (such as CO_2 leakage in the case of CCS), explosion risk (as for biogas plants if not properly supervised), nuclear accidents risks, risk of flood (when a dam breaks for example), the risks related to working conditions for workers in this sector, etc.

Other human ecology impacts

This related to impacts such as wind turbines generating noise or shadows, or smells from biogas infrastructure may generate smells, possible population displacements but also possible recreational areas or irrigation support when a dam is installed, etc.

8. How to use the tables: indicative instructions

First, the scenario producers lists the technologies with the desired **level of granularity** (one or two types of wind power or solar PV, two or three types of hydropower, etc.), with justifications for these distinctions and possible explanations for why certain technologies are not taken into account (e.g., for of robustness reasons).

Then, the tables are intended to be flexible: each scenario producer decides both which boxes will be filled in and what should be included in it (a value, a qualitative estimate, a reference to a paragraph of the report, etc.) Each of the five tables can be presented either once for the entire study, or for each scenario (for example according to the number of characteristics that are modified between the scenarios).

We suggest to fill in the table as follows:

- First for the **rows**, enter all the technologies used for the construction of the scenario mix. A justification for this choice of possible technologies is welcomed. *Why this list of technologies? Have any technologies been deliberately exclued? Is a TRL or CRI criterion used?*

- Then for the **columns**, ignore those that do not concern any of the technologies in the scenario. This means these characteristics are not useful in the study to determine the supply-side mix. These columns can be grayed out, or filled with an indication such as "not used". Each column can be subdivided for greater granularity of information if needed. Similarly, columns can be added if characteristics useful in the study do not appear in these templates.

- Finally, for the **all other boxes**, each can be seen as one paragraph in which the characteristic can be filled in and explained. In each case, since these data are normally already processed in the scenario, it is possible to simply refer to the corresponding paragraph in the report. Here is a list of useful items of information that can be introduced:

- **Is this value unused or confidential?** In this case, it is useful to indicate it with a mention *(like "not used" or "confidential").*

- **Otherwise, what is the given value?** It can be quantitative or qualitative.

- **How is it determined?** If it is exogenous, the source can be presented (workshop, literature, discussion with industry stakeholders, academics, other expert opinions, etc.). If endogenous, the calculation mode is relevant. Indeed, each variable can be a hypothesis or an outcome, depending on the scenarios. It is up to the scenario producer to choose how to introduce them. Also, some characteristics can sometimes be used for storytelling purposes only (i.e., they are not used when determining the supply-side mix). This can also be interesting information. In addition, the units used may be specified as it can change from one technology to another. Also, if the variable is an aggregate (e.g., "OPEX"), what is contained may be explained.

- **Does the variable change during the scenario?**

- **Which explanatory elements?** What substantiates the consistence of the value and its evolution? Narrative elements can be provided. E.g., for an unspecified value: « this variable is redundant with others » (as other combined quantities already enable to get the same information), or « this quantity is outside the scope of the study driving question and is therefore not useful », etc.

NB: every study already disclose this type of information for some given characteristics. The idea here is to generalize this type of practice and to centralize information in a single place.

Here is a short example for a fictional study:

	TRL	Unitary capacity	Efficiency of new plants	Life duration (years)	Load factor	...
PV		See paragraph 2.1		25		
Wind		See paragraph 2.2		30 Repowering has been considered (see p44)		
Hydro	Not used	See paragraph 2.3	Not used. See p105	50	Confidential data	
Nuclear		See paragraph 2.4		40 See paragraph 3.4 for more details		
Coal		See paragraph 2.5		40		
Gas		See paragraph 2.6				

Figure 10: In this fictional study, six power generation technologies are considered. The first characteristic, the TRL, is never used. The unit capacity is described in respective paragraphs for each technology. The plants energy yield is not a used but some consideration on it are provided in one part of the report, possibly to explain why it is not a useful characteristic here. Life durations are specified, with additional details for wind and nuclear power. Load factors are used but the information is confidential. Finally, the study goes into an in-depth analysis of gas-fired power plants, and dedicates a paragraph to it that explores considerations about on several characteristics and the links between them.

C. The grid

1. In ETS, transmission grid reinforcement is sometimes studied, distribution grid evolution is never studied

The transmission grid is rarely finely modeled. Some studies models it as a fictional single node (copperplate model), as if all plants and consumers were connected all together at a single point (ADEME, 2012; Association négaWatt, 2014). The hourly load-supply balance can be checked with these simplified models if load is properly modeled (taking into account the spatial variability of load, for example as a function of different temperatures, winds and weather conditions) as well as supply (which also has a spatial variability, all the more important with larger shares of VRES).

When transmission grid needs to be modified because of significant changes in load and/or supply levels and/or location, models with the adequate spatial resolution are required (IRENA, 2017). Basic transmission grid models depicts it as links between individual nodes representing countries, or regions interconnected with each other. For example, (ADEME, 2015) models the transition network as links between regions representing the inter-region electricity flows, providing information on the necessary reinforcements of transmission between regions. Scenarios using PRIMES model (such as (ECF, 2010; European Commission, 2011; European Commission, 2016; SFEN, 2018)) model the transmission grid through links between countries, which are themselves represented as single nodes (E3MLab, 2017). This model can provide information about interconnection strengthening needs, but no information about grid requirements within each country.

A few models finely model the transmission grid (RTE, 2017) in order to get precise information about where and how the grid should evolve.

Distribution networks are not modelled in national, supra-national or world long-term models.

Recommendations to scenario producers

For scenarios requiring significant changes in the transmission or distribution grids (e.g. a shift to a decentralized network, or significant changes in the production locations), the various impacts should be estimated using a tool which represents finely enough the grid and its evolutions.

If the architecture of the network evolves, each transition state should be represented in order to assess the PS performances over the scenario timeframe, making sure that no transition state of the PS lead to power supply collapse.

2. Interconnections

Interconnections are the links between different, relatively autonomous, power systems. These new links imply a certain level of coupling between both PS.

Interconnections are characterized by their power transmission capacity, their voltage level and their current form (Alternative current or Direct current).

They are composed of two substations transforming the current into the proper form and at the proper voltage, and high voltage lines in between. For High Voltage Direct Current (HVDC) lines, the main cost component is the substations; hence HVDC lines are economically interesting for long distances (International Energy Agency, 2016).

Three different installation methods exist: overhead lines, underground lines and subsea lines. Overhead lines cost significantly less than underground lines, but they encounter more acceptance issues than underground lines.

Depending on these characteristics, the services provided, and the technology risks are different.

- **AC interconnections** lead to a complete coupling between both PSs. Hence a common frequency control and joint protection systems must be implemented. These interconnections require solidarity between interconnected PSs.
- On the contrary, **DC interconnections** propose more independence between the interconnected PSs: connected PSs can have different frequencies and voltages (International Energy Agency, 2016). However, compared to AC interconnections, they generate harmonics and reactive power must be generated at converter stations (see PS operation section) (Felix Wu, 2001).

Recommendations to scenario producers

Transparency on the type of interconnection which are implemented in the scenario should be achieve. The following aspects should be considered:

- Type of power transmission (AC or DC)
- Type of line which is used (overhead, underground, subsea)

More considerations on interconnections can be found in the Boundary Conditions section.

Annexes

A. Examples (among others) of how some future studies use transparency tables

These are just a few of numerous examples that can be found in future studies. We present them here to provide concrete illustrations of the use of transparency tables:

- (Greenpeace, 2015) provides detailed information on their hypotheses about the cost evolution of renewable electricity technologies, including the corresponding data sources:

"Assumptions on future costs for renewable electricity technologies in the Energy [R]evolution scenario of 2012 were derived from a review of learning curve studies, for example by Lena Neij,[21] from the analysis of technology foresight and road mapping studies, including the European Commission funded NEEDS project (New Energy Externalities Developments for Sustainability)[22] or the IEA Energy Technology Perspectives 2008, projections by the European Renewable Energy Council published in April 2010 ("Re- Thinking 2050") and discussions with experts from different sectors of the renewable energy industry. for the new Energy [R]evolution, cost decreases due to recent market developments are taken into account, leading to changes in own cost assumptions above all for photovoltaics and solar thermal power plants (including heat storages). However, for the reason of consistency, region-specific cost assumptions from WEO 2014 are adopted for biomass power plants, hydro, wind power and ocean energy. The following tables exemplarily show data used for the region OECD Europe."

This is one of the many tables provided :

TABLE 5.13 | OVERVIEW OF EXPECTED INVESTMENT AND OPERATION & MAINTENANCE COSTS PATHWAYS FOR HEATING TECHNOLOGIES IN EUROPE

	UNIT	2012	2020	2030	2040	2050
GEOTHERMAL DISTRICT HEATING*	$/kW	2,650	2,520	2,250	2,000	1,760
HEAT PUMPS	$/kW	1,990	1,930	1,810	1,710	1,600
LOW TECH SOLAR COLLECTORS	$/kW	140	140	140	140	140
SMALL SOLAR COLLECTOR SYSTEMS	$/kW	1,170	1,120	1,010	890	750
LARGE SOLAR COLLECTOR SYSTEMS	$/kW	950	910	810	720	610
SOLAR DISTRICT HEATING*	$/kW	1,080	1,030	920	820	690
LOW TECH BIOMASS STOVES	$/kW	130	130	130	130	130
BIOMASS HEATING SYSTEMS	$/kW	930	900	850	800	750
BIOMASS DISTRICT HEATING*	$/kW	660	640	600	570	530

* Without network

- (Lappeenranta University of Technology / Energy Watch Group, 2017) provides its own transparency tables, for generation units, storage units, and transmission lines:

  - Generation units table (only a part of it)

Table 2.2: *Technical and financial assumptions of energy system technologies used in the energy transition from 2015 to 2050. Assumptions are taken from Pleßmann et al. (48) and European Commission (49) and further references are individually mentioned. All technical and financial assumptions are given in currency values of the year 2015.*

Technologies		Units	2015	2020	2025	2030	2035	2040	2045	2050	REF
PV rooftop – residential	Capex	€/kW$_{,el}$	1360	1169	966	826	725	650	589	537	50
	Opex fix	€/(kW$_{,el}$ a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	€/(kWh$_{,el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV rooftop - commercial	Capex	€/kW$_{,el}$	1360	907	737	623	542	484	437	397	50
	Opex fix	€/(kW$_{,el}$ a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	€/(kWh$_{,el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV rooftop - industrial	Capex	€/kW$_{,el}$	1360	682	548	459	397	353	318	289	50
	Opex fix	€/(kW$_{,el}$ a)	20	17,6	15,7	14,2	12,8	11,7	10.7	9.8	
	Opex var	€/(kWh$_{,el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV optimally tilted	Capex	€/kW$_{,el}$	1000	580	466	390	337	300	270	246	50
	Opex fix	€/(kW$_{,el}$ a)	15	13.2	11.8	10.6	9.6	8.8	8.0	7.4	
	Opex var	€/(kWh$_{,el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV single-axis tracking	Capex	€/kW$_{,el}$	1150	638	513	429	371	330	297	271	50,106
	Opex fix	€/(kW$_{,el}$ a)	17.3	15.0	13.0	12.0	11.0	10.0	9.0	8.0	
	Opex var	€/(kWh$_{,el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
Wind onshore	Capex	€/kW$_{,el}$	1250	1150	1060	1000	965	940	915	900	107
	Opex fix	€/(kW$_{,el}$ a)	25	23	21	20	19	19	18	18	
	Opex var	€/(kWh$_{,el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	25	25	25	25	
CSP (solar field, parabolic trough)	Capex	€/kW$_{,th}$	547.8	427.8	369.2	326.9	304	283.6	265.4	249.5	54,55
	Opex fix	€/(kW$_{,th}$ a)	12.6	9.8	8.5	7.5	7	6.5	6.1	5.7	
	Opex var	€/(kWh$_{,th}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	30	30	30	30	
Geothermal power	Capex	€/kW$_{,el}$	5250	4970	4720	4470	4245	4020	3815	3610	56,49
	Opex fix	€/(kW$_{,el}$ a)	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	
	Opex var	€/(kWh$_{,el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	40	40	40	40	40	40	40	40	
Water electrolysis	Capex	€/kW$_{,H2}$	800	685	500	363	325	296	267	248	57,58
	Opex fix	€/(kW$_{,H2}$ a)	32	27	20	12.7	11.4	10.4	9.4	8.7	
	Opex var	€/(kWh$_{,H2}$)	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	
	Lifetime	years	30	30	30	30	30	30	30	30	
Methanation	Capex	€/kW$_{,CH4}$	492	421	310	278	247	226	204	190	57,58
	Opex fix	€/(kW$_{,CH4}$ a)	19.7	16.8	12.4	11.1	9.9	9.0	8.2	7.6	
	Opex var	€/(kWh$_{,CH4}$)	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	
	Lifetime	years	30	30	30	30	30	30	30	30	

- Storage units table

Table 2.3: *Energy to power ratio and self-discharge rates of storage technologies. Efficiency values are given for 2015.*

Technology	Efficiency [%]	Energy/Power Ratio [h]	Self-Discharge [%/h]	References
Battery	90	6	0	62, 108
PHS	85	8	0	49
A-CAES	54	100	0.1	49
TES	90	8	0.2	48
Gas storage	100	80*24	0	48

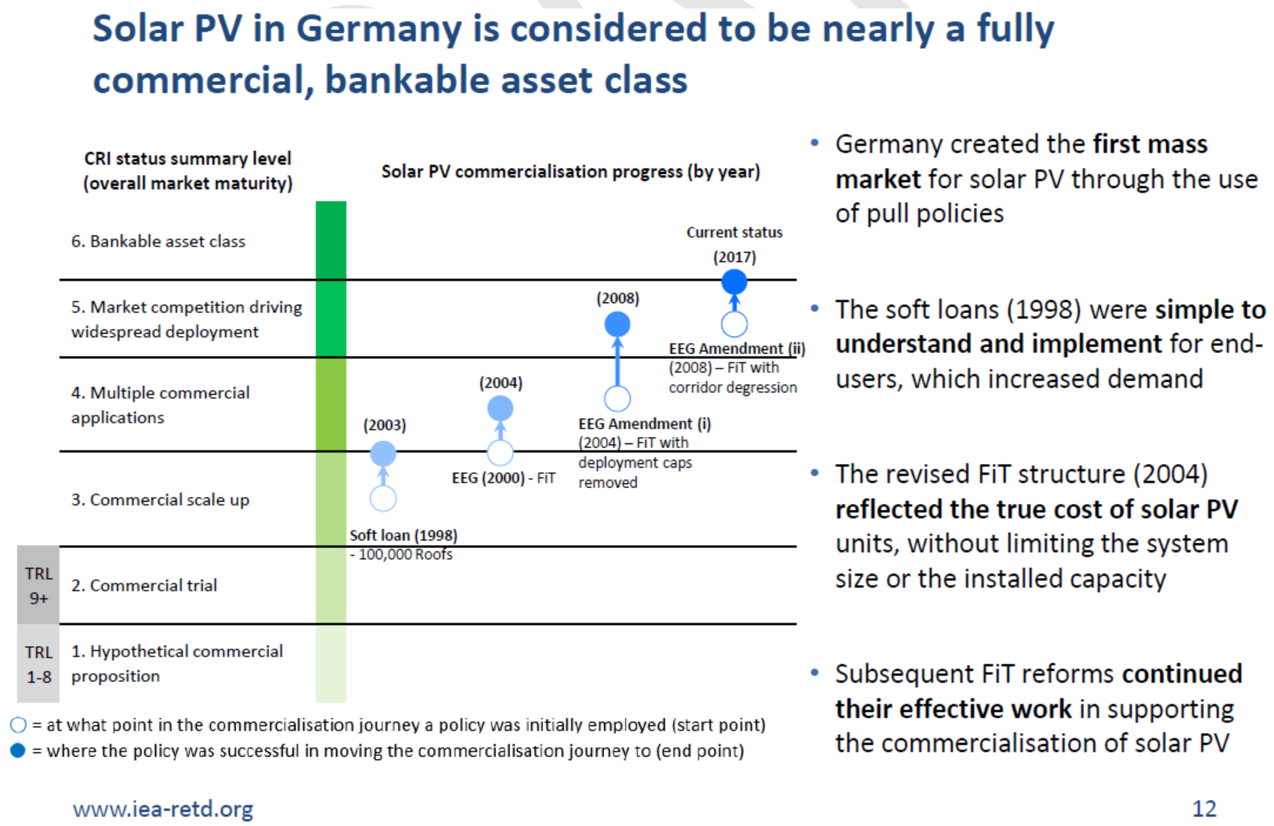
- Transmission lines table

Table 2.5: *Efficiency assumptions for HVDC and HVAC transmission for all years 112.*

Component	Power losses
HVDC line	1.6 % / 1000 km
HVDC converter pair	1.4%
HVAC line	9.4 % / 1000 km

B. Further information about Commercial Readiness Index (CRI)

(IEA-RETD, 2017) provides a table showing the CRI evolution of solar PV in Germany:



Here is a table summarizing some of (IEA-RETD, 2017) main conclusions:

Our case studies show the value of the CRI as a tool for communicating the importance of market conditions beyond technical performance for RETs

Advantages	Limitations
• The CRI helps to **prompt policy makers** to consider a range of **factors** that influence the commercial and market readiness of RETs • The CRI can help to **identify the main barriers** that need to be addressed in order to help RETs to be developed and widely deployed • **It can be used to Illustrate historically** which policies have affected the performance of certain indicators	• The CRI does not explain **how** and **why** policies are effective • It only provides a **historical snapshot** of the overall commercial maturity at one point in time • It **does not indicate** to policy makers **what are the potential interventions** that could be used to support the RETs • It is **difficult to translate policy lessons** from one context to another • The CRI assessment is **subjective** since it is based on qualitative criteria

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C. Environmental characteristics tables from (United States Department of Energy, 2015)

(United States Department of Energy, 2015) is the 2015 Quadrennial Technology Review (QTR) from U.S. Department of Energy. It examines the status of the science and energy technology with a focus on technologies with commercialization potential in the midterm and beyond. In the chapter 10 of the study – "Concepts in Integrated Analysis" – five tables about the following environmental characteristics are presented: material requirements, land use, water use, GHG emissions and air pollutants emissions. This can be a good example of data that could be used in the table of environmental characteristics.

Table 10.4 Range of materials requirements (fuel excluded) for various electricity generation technologies[52]

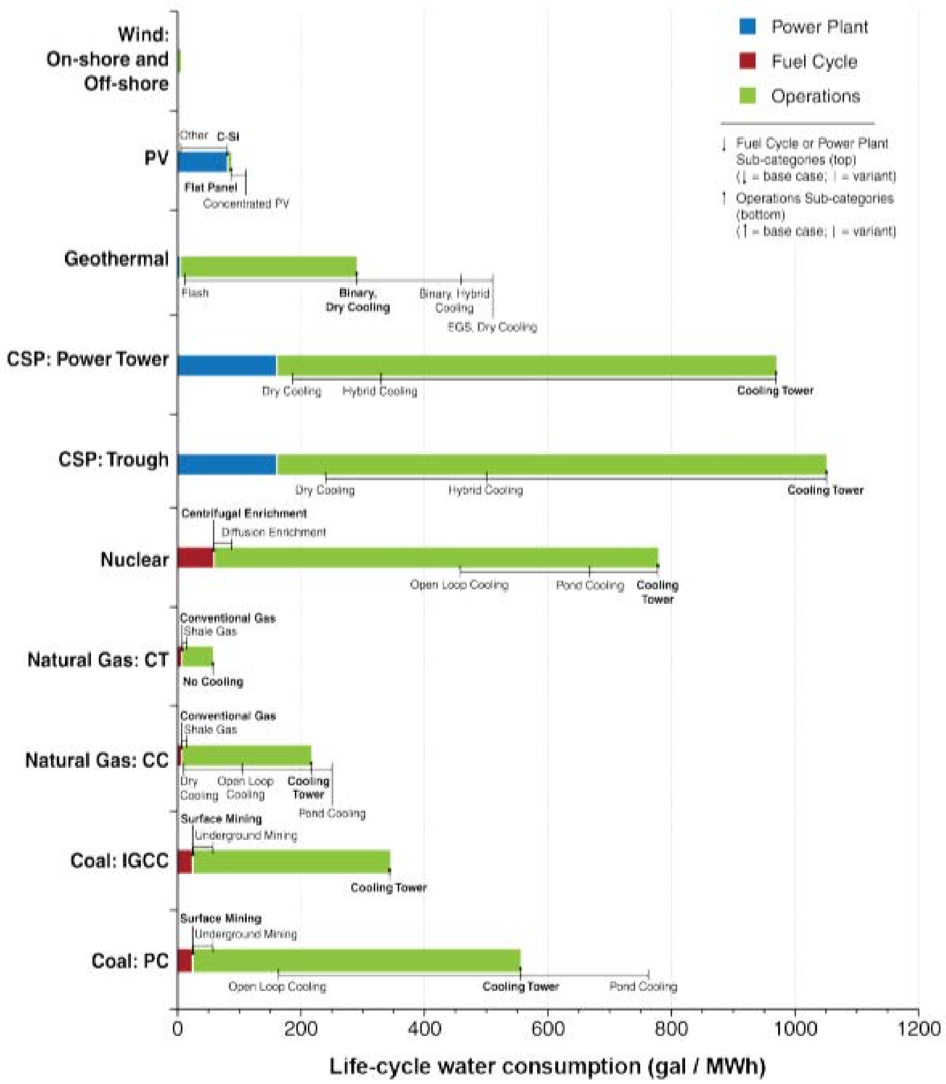
Materials (ton/TWh)	Generator only				Upstream energy collection plus generator			
	Coal	NGCC	Nuclear PWR	Biomass	Hydro	Wind	Solar PV (silicon)	Geothermal HT binary
Aluminum	3	1	0	6	0	35	680	100
Cement	0	0	0	0	0	0	3,700	750
Concrete	870	400	760	760	14,000	8,000	350	1,100
Copper	1	0	3	0	1	23	850	2
Glass	0	0	0	0	0	92	2,700	0
Iron	1	1	5	4	0	120	0	9
Lead	0	0	2	0	0	0	0	0
Plastic	0	0	0	0	0	190	210	0
Silicon	0	0	0	0	0	0	57	0
Steel	310	170	160	310	67	1,800	7,900	3,300

Key: **NGCC** = natural gas combined cycle; **PWR** = pressurized water reactor; **PV** = photovoltaic; **HT** = high temperature

Table 10.2 Representative Land Use Energy Intensity Estimates for a Variety of Electricity Generating Technologies[47] (Note that these estimates are from different studies and are not comparable as they use different assumptions for what is included and how it is included—i.e., they are not harmonized)

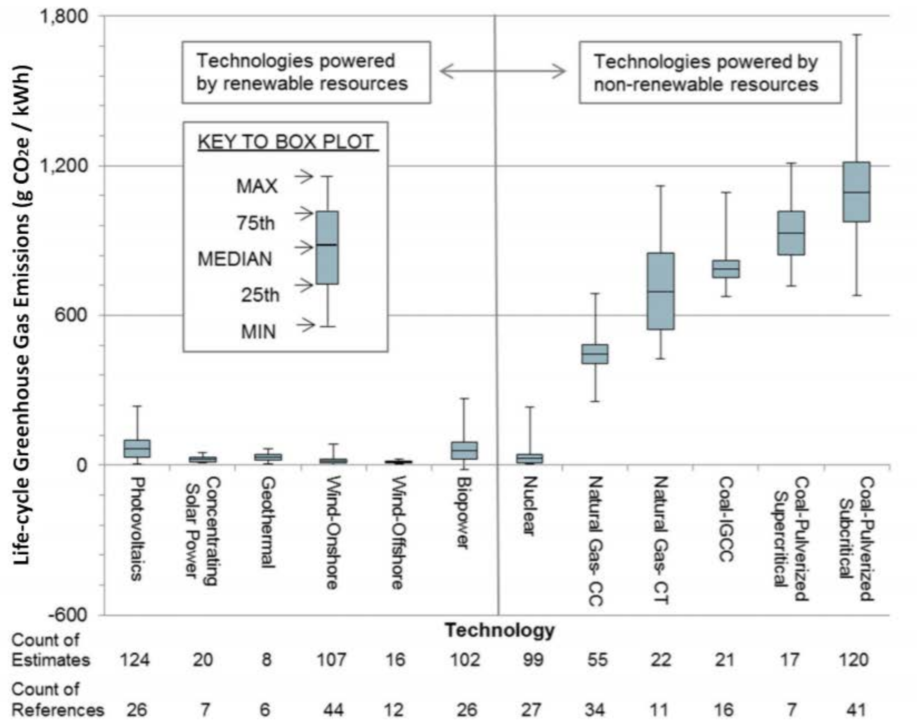
Energy technology	m^2/MW	System boundary Power plant site only; does not consider energy resource mining or collection, processing, or transport area, or land used for waste disposal
Biomass: direct-fired	9,000–45,000	Power plant site only
Coal	270–8,000	Power plant site only
Coal: CCS	12,000	Power plant site only
Nuclear	6,700–13,800	Low estimate is site only. High estimate includes transmission lines, water supply, and rail lines, but does not include land used to mine, process, or dispose of wastes.
Energy technology	**m^2/MW**	**System boundary Energy resource extraction area plus power plant site**
Biomass: gasification	3,000,000	Site and crop area. Area used primarily driven by biomass productivity and power plant efficiency.
Coal (site and upstream)	40,000	Site and strip mining included
Geothermal: hydrothermal	1,200–150,000	Low estimate is for the site only. Upper estimate includes well-field and plant.
Geothermal: hot dry rock	4,600–17,000	Includes well-field and plant
Hydropower: reservoir	20,000–10,000,000	Site of generators and reservoir
Solar: PV	10,000–60,000	Site of PV system, which includes the area for solar energy collection. PV systems on pre-existing structures have essentially no net increase in land use.
Solar: thermal	12,000–50,000	Site of concentrating solar thermal system, which includes the area for solar energy collection
Wind	2,600–1,000,000	Low-end value is for the site only, which includes the physical footprint of the turbines and access roads. The high-end value includes the land area between turbines, which is typically available for farming or ranching (see Section 10.5.7).

Figure 10.3 Life Cycle Water Consumption Estimates for Various Electricity Generation Technologies[44]



Notes: Not all cooling options are shown; for instance, more expensive, dry cooling (with zero water consumption and withdrawal) is an option for most plants. Key: **PV** = solar photovoltaic; **C-Si** = crystalline silicon; **EGS** = enhanced geothermal system; **CSP** = concentrating solar power; **CT** = combustion turbine; **CC** = combined cycle; **IGCC** = integrated gasification combined cycle; and **PC** = pulverized coal, sub-critical.

Figure 10.2 Illustrative Comparison of Life-Cycle GHG Emissions of Various Electricity Generation Technologies[32]



Note: Reference has "harmonized" original data to correct for differences in a number of input assumptions, resulting in reduced variance. "Count of estimates" refers to the number of separate sources of data. "Count of references" refers to the number of separate studies used to provide data. Key: **CC** = combined cycle; **CT** = combustion turbine; and **IGCC** = integrated gasification combined cycle.

Table 10.1 National Average Energy Efficiencies, Technology Shares for Each Fuel Type, and Criteria Air Pollutant Emission Factors (g/kWh) of the U.S. Power Sector in 2010[37]

Fuel type, combustion technology	Efficiency	Technology shares	NO_x	SO_x	PM_{10}	$PM_{2.5}$	CO	VOC
Biomass, ST	21.9%	100.0%	0.9267	0.603	2.814	1.9763	4.7546	0.1349
Coal, IGCC	34.8%	0.1%	0.1167[a]	0.0403[a]	2.4693	0.7198	0.02191	0.0012
Coal, ST	34.7%	99.9%	1.141	3.1998	0.2836	0.1994	0.1221	0.0147
NG, CC	50.6%	82.1%	0.1175	0.0041	0.0009	0.0009	0.098	0.0018
NG, GT	31.6%	5.5%	0.3452	0.0172	0.0386	0.0386	0.4458	0.0114
NG, ICE	32.8%	0.9%	3.0829a	0.0061[a]	0.4718	0.4718	3.8187	1.1102
NG, ST	32.3%	11.5%	0.8653	0.1745	0.0426	0.0426	0.4821	0.032
Oil, GT	29.4%	18.2%	2.9759	0.9438	0.3011	0.0763	0.0181	0.003
Oil, ICE	36.3%	4.6%	4.7442a	0.2274[a]	0.0138	0.013	0.0315	0.0119
Oil, ST	33.0%	77.2%	4.4825	7.6442	0.1797	0.1395	0.1676	0.0216

Notes: Plant-level (not life-cycle) emissions. Technology share is the ratio of the amount of electricity generated by each technology to the total electricity generation by fuel type. Key: **NO_x** = nitrogen oxides, **SO_x** = sulfur oxides, **PM_{10}** = 10 µm particulate matter, **$PM_{2.5}$** = 2.5 µm particulate matter, **CO** = carbon monoxide, **VOC** = volatile organic carbon, **ST** = steam turbine, **IGCC** = Integrated Gasification Combined Cycle, **NG** = natural gas, **CC** = combined cycle, **GT** = gas turbine, **ICE** = internal combustion engine.

[a] Adjusted based on averaged 2007 emission factors for coal IGCC, NG ICE or oil ICE as appropriate, and the 2007 to 2010 emission reduction rates of NO_x and SO_x for coal-, NG- or oil-fired power plants, respectively.

Bibliography

ADEME. (2012). *L'exercice de prospective de l'ADEME - « Vision 2030-2050 »*.

ADEME. (2014). *Visions énergie climat 2030/2050 - Quels modes de vie pour demain ?* (Nº 8102; p. 132).

ADEME. (2015). *Un mix électrique 100% renouvelable ? Analyses et optimisations*.

ADEME / Artelys. (2015). *Un mix électrique 100% renouvelable ? Analyses et optimisations - Hypothèses de réseau et description du modèle*.

ADEME / Artelys. (2018). *Trajectoires d'évolution du mix électrique 2020-2060 - Synthèse*.

Agora Energiewende, IDDRI. (2018). *L'Energiewende et la transition énergétique à l'horizon 2030*.

ANCRE. (2017). *Scénario « Loi de Transition Energétique pour la Croissance Verte »* (p. 8).

ARENA. (2014). *Technology Readiness Levels for Renewable Energy Sectors*. Consulté à l'adresse https://www.arena.gov.au/assets/2014/02/Technology-Readiness-Levels.pdf

ARTELYS / European Commission. (2017). *METIS Technical Note T6 - METIS Power SYstem Module* (p. 43).

Association négaWatt. (2014). *Scénario négaWatt 2011-2050 - Hypothèses et méthode*.

Association négaWatt. (2017). *Scénario négaWatt 2017-2050 | Dossier de synthèse* (p. 48).

Barnacle, M., Robertson, E., Galloway, S., Barton, J., & Ault, G. (2013). Modelling generation and infrastructure requirements for transition pathways. *Energy Policy*, *52*, 60-75. https://doi.org/10.1016/j.enpol.2012.04.031

Barton, J., Davies, L., Dooley, B., Foxon, T. J., Galloway, S., Hammond, G. P., … Thomson, M. (2018). Transition pathways for a UK low-carbon electricity system: Comparing scenarios and technology implications. *Renewable and Sustainable Energy Reviews*, *82*, 2779-2790. https://doi.org/10.1016/j.rser.2017.10.007

Boston, A. (2013). Delivering a secure electricity supply on a low carbon pathway. *Energy Policy*, *52*, 55-59. https://doi.org/10.1016/j.enpol.2012.02.004

Brouwer, A. S., van den Broek, M., Zappa, W., Turkenburg, W. C., & Faaij, A. (2016). Least-cost options for integrating intermittent renewables in low-carbon power systems. *Applied Energy*, *161*, 48-74. https://doi.org/10.1016/j.apenergy.2015.09.090

DGEC/CGDD/ADEME. (2015). *Scénarios prospectifs Energie - Climat - Air pour la France à l'horizon 2035*.

Dii. (2012). *Perspectives on a Sustainable Power System for EUMENA*.

E3MLab. (2017). *PRIMES Model, Version 6, 2016-2017 - Detailed model description*.

ECF. (2010). *Roadmap 2050 - A Practical Guide to a Posperous, Low-Carbon Europe*.

EDF. (2015). *Technical and economic analysis of the European electricity system with 60% RES*.

Engel, D. W., Dalton, A. C., Anderson, K. K., Sivaramakrishnan, C., & Lansing, C. (2012). *Development of Technology Readiness Level (TRL) Metrics and Risk Measures* (Nº PNNL-21737, 1067968). https://doi.org/10.2172/1067968

ENTSO-E. (2015). *TYNDP 2016 Scenario Development Report*.

European Commission. (2011). *Energy Roadmap 2050 - Impact assessment and scenario analysis*.

European Commission. (2016). *EU reference scenario 2016: energy, transport and GHG emissions : trends to 2050.* Luxembourg.

Felix Wu. (2001, mai). *Technical Considerations for Power Grid Interconnection in Northeast Asia*. Présenté à Beijing, China. Beijing, China.

Foxon, T. J. (2013). Transition pathways for a UK low carbon electricity future. *Energy Policy*, *52*, 10-24. https://doi.org/10.1016/j.enpol.2012.04.001

France Stratégie. (2017). *Energie centralisée ou décentralisée ?* (p. 4).

Fraunhofer ISE. (2015). *What will the energy transformation cost? - Pathways for transforming the German energy system by 2050*.

Greenpeace. (2012). *Energy [R]evolution - A sustainable world energy outlook 2012* (p. 340).

Greenpeace. (2015). *Energy [R]evolution - A sustainable world energy outlook 2015* (p. 364).

Hache, E., & Palle, A. (2018). *Intégration des énergies renouvelables variables dans le système électrique : analyse bibliométrique et enquêtes auprès des acteurs*. 18.

Hammond, G. P., Howard, H. R., & Jones, C. I. (2013). The energy and environmental implications of UK more electric transition pathways: A whole systems perspective. *Energy Policy*, *52*, 103-116. https://doi.org/10.1016/j.enpol.2012.08.071

Hammond, G. P., & Pearson, P. J. G. (2013). Challenges of the transition to a low carbon, more electric future: From here to 2050. *Energy Policy*, *52*, 1-9. https://doi.org/10.1016/j.enpol.2012.10.052

Ibrahim, H., Ilinca, A., & Perron, J. (2008). Energy storage systems—Characteristics and comparisons. *Renewable and Sustainable Energy Reviews*, *12*(5), 1221-1250. https://doi.org/10.1016/j.rser.2007.01.023

IEA. (2015). *Energy Technology Perspective*.

IEA-RETD. (2017). *Commercial Readiness Index Assessment*. Consulté à l'adresse https://www.carbontrust.com/media/674417/iea-retd-tcp-commercial-readiness-index-assessment.pdf

International Energy Agency. (2016). *Large-Scale Electricity Interconnection - Technology and Prospects for Cross-Regional Networks* (p. 36).

International Energy Agency. (2018). *World Energy Model Documentation - 2018 Version* (p. 82).

IRENA. (2017). *Planning for the Renewable Future - Long-term Modelling and Tools to Expand Variable Renewable Power in Emerging Economies*.

JRC. (2014). *Energy Technology Reference Indicator (ETRI) projections for 2010-2050.*

Keramidas, K., Kitous, A., Schmitz, A., European Commission, & Joint Research Centre. (2017). *POLES-JRC model documentation.*

OECD/IEA. (2017). *World Energy Outlook 2017* (p. 782).

RTE. (2017). *Bilan prévisionnel de l'équilibre offre-demande d'électricité en France*.

SFEN. (2018). *Le nucléaire français dans le système énergétique européen*.

United States Department of Energy. (2015). *Quadrennial Technology Review An Assessment Of Energy Technologies And Research Opportunities - Chapter 10: Concepts in Integrated Analysis* (p. 39).

Véronique Beillan, Caroline Bono, Sophie Bouly De Lesdain, & Fabien Bricault. (2018). *Les systèmes électriques de demain - Un défi pour la transition énergétique*. Tec & Doc Lavoisier.

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The Shift Project

The Shift Project, a non-profit organization, is a French think-tank dedicated to informing and influencing the debate on energy transition in Europe. The Shift Project is supported by European companies that want to make the energy transition their strategic priority & by French public funding.

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Power system operation in energy transition scenarios

Technical file #7 – Draft version

Information and recommendations for scenario producers

This document is part of a set of 12 technical files. These files have been produced by *The Shift Project* after one year and a half of research and experts consultations on the different aspects of energy transition and the future studies around these aspects.

Our project, "Power Systems 2050 – Guidelines for design," started in January 2018, with the participation of 10 experts who defined the key subjects which according to them have to be collectively tackled by future studies about the power transition. *The Shift Project* then investigated each of these subjects, consulting in total 40 experts, organizing 4 workshops, and reviewing a large bibliography, including a dozen of future studies about power (and energy) transition at different geographical scales.

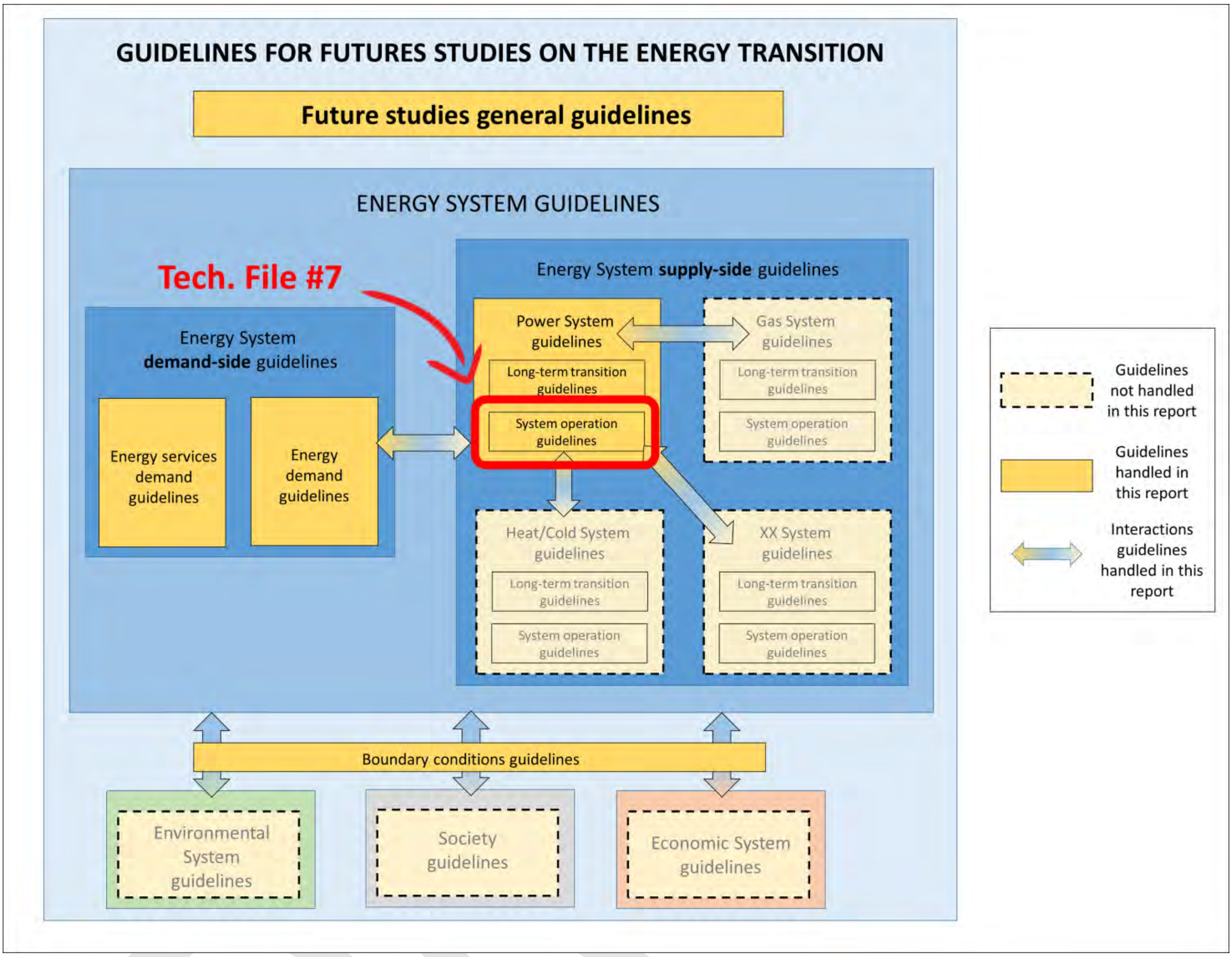
The goal of this project is to produce a set of guidelines addressed to scenario producers. These guidelines seek to foster transparency and consistency *within* future studies and to develop a common language *across* studies. By defining a number of important items which are key to deal with in future studies, we actually propose a study template which enables a better understanding of the location of each proposed scenario on the tree of possible transitions. Once again, the objective is not to *rank* studies, or scenarios, but rather to *compare* them to get a better collective overview of the different aspects of the transition (what are the differences between studies in terms of driving questions, hypotheses, models, methodology, results?).

Several aspects of the energy transition are handled in these technical files. However, on the energy supply-side only the power system has been studied. The main reason for this choice is that we had to start from somewhere with limited resources, and the power system seemed to be a key system to study in the energy transition context, towards a low-carbon economy, as shown by the growing number of future studies focusing on this system. However, the guidelines we propose could be completed by analyzes on the other energy supply-side systems (the gas system, oil system, heat system and so on).

Each technical file tackles several aspects of future studies for the power (and energy) transition. Here is the complete list of the technical files produced during the project:

#	Technical file title
1	Future studies on the energy transition
2	Energy transition models
3	Boundary conditions for energy transition scenarios
4	Long-term evolution of energy consumption in energy transition scenarios
5	Lifestyles and consumption behaviors in energy transition scenarios
6	Long-term evolution of the power system supply-side in energy transition scenarios
7	Power system operation in energy transition scenarios
8	Impact assessment in energy transition scenarios
9	Transition desirability in energy transition scenarios
10	Environmental assessment of energy transition scenarios
11	Economic evaluation of energy transition scenarios
12	Employment assessment of energy transition scenarios

Altogether, these files cover the fields described on the following map of the guidelines for future studies on the energy transition. The document you are reading covers the red-circled topics.



In addition to these technical files, three complementary notes have been produced as specific focuses on the following aspects: material criticality in energy transitions (in French, to be translated and added to technical file #10), levelized cost of electricity (LCOE) in energy transition future studies (in French) and discount rate in energy transition future studies (in French).

We warmly thank the experts who participated in this project by putting forward ideas and critiques, references and documents, and who accepted to discuss these ideas with us and other experts:

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Table of content

Reading keys

Explanation box, containing key information for a better overall understanding of the subjects.

Recommendations to scenario producers:

These boxes contain the recommendations for scenario producers.

The word "should" means that scenario producers, if they are to follow the guidelines, must substantiate the corresponding point. The words "may" or "might" relates to suggestions, ideas to help the scenario producer respond to the point.

Questions in italic are examples of questions scenario producers might ask to substantiate the points. They are here in an illustration purpose.

Phrases in italic relate words which are being defined and will be subsequently used in the framework.

Phrases which are highlighted in yellow refer to other technical documents of this series.

I. System reliability is ensured by a set of key services

"Reliability of a power system refers to the probability of its satisfactory operation over the long run. It denotes the ability to supply adequate electric service on a nearly continuous basis, with few interruptions over an extended time period. Security of a power system refers to the degree of risk in its ability to survive imminent disturbances (contingencies) without interruption of customer service. It relates to robustness of the system to imminent disturbances and, hence, depends on the system operating condition as well as the contingent probability of disturbances. Stability of a power system refers to the continuance of intact operation following a disturbance. It depends on the operating condition and the nature of the physical disturbance." (IRENA, 2017)

Concretely, PS reliability is ensured by considering that the higher the probability of a failure, the lower its adverse consequences (which can be measured in undelivered MWs) must be[1] (RTE, 2004).

In Europe, countries have different ways to measure reliability, either through probabilistic assessment (in %) or through a deterministic one (yes or no). For example, in France, Belgium and the UK, a 3 hour/annum standard is set (corresponding to a 99.97% reliability). In other words, the objective is that nobody is cut from power during the whole year, except for three hours at maximum.

PS malfunction can be caused by:

- Consumption or generation variation
- Weather events (thunder, gale, frost, flood, hot or cold weather,…)
- Technical failures or aggression from outside
- Human mistakes in the operation or maintenance of the system

(RTE, 2004)

Such contingency events are driven primarily by factors independent of VRE-specific qualities, such as the loss of a large generator (renewable or conventional), transmission line or sub-station in the power system. The ability to return to a state of normal operation following a contingency event is referred to as "stability". While deployment of VRE does not necessarily influence the occurrence of contingency events, it changes the system's ability to remain stable (IRENA, 2017).

These events can lead to disturb some key electric parameters which must remain stable: frequency, voltage, and rotor angle.

- Frequency stability: Ability of a power system to balance active power that is, to balance generation and load (also called respectively supply and demand), which is equivalent to maintain frequency.
- Voltage stability: Ability of a system to maintain a steady state voltage at all bus bars, in normal operation or following a disturbance. This is equivalent to balance reactive power along the PS.
- Rotor angle stability: Ability of the synchronous machines in an interconnected power system to remain in synchronism after being subjected to a disturbance.

(BMZ Deutsche GIZ GmbH, 2013; IRENA, 2017)

These parameters, the consequences of their instabilities and their potential evolutions in scenarios are described in the following sections.

In order to control frequency, voltage and rotor angle synchronism, the architecture of the corresponding control system is composed of sensory organs, decision organs and actuation organs. These organs can be mechanical, electrical, electronical or numerical and they can be more or less concentrated on some equipment of the PS.

[1] This is known as the N-k rule

The fault[2] detection system supporting the PS and acting as its sensory organ for detecting faults must correctly operate for the PS to react fast enough to fix or isolate faults. Currently, generation units must provide enough fault current and be equipped with fault ride through capability for the detection system to operate correctly.

Finally, if frequency, voltage, or rotor angle control systems fail, this leads to a PS failure: local power outages, or total system blackout. In this case the PS must be able to restart as quickly as possible (which can take several hours to several tens of hours whereas minor control faults are solved within minutes to tens of minutes). This is the black start capability.

The different capabilities of the PS and its components enabling its proper operation are called ancillary services.

II. Frequency stability

A. Ensuring the balance between electricity supply and demand at all times: a matter of frequency

Frequency stability[3] reflects the fact that the global balance between supply and demand is achieved at all times. In case supply is lower than demand, spinning machines (also called synchronous machines) slow down hence system frequency decreases. On the contrary, if supply is greater than demand, spinning machines speed up hence system frequency increases (RTE, 2004).

Frequency variations can be caused by:

- Increase or decrease of supply
- Increase or decrease of demand
- faults of equipment, or human error, on the power system (e.g. the unexpected shutdown of a generation plant, or the disconnection of a high voltage line)

The consequences of frequency variations can be severe: inability to use the electricity vector if frequency is too different than 50 Hz (frequency reference value in Europe); damages to the electric devices plugged to the network; emergency shutdown of generation plants leading to total or partial power system collapse (RTE, 2004).

B. Flexibility is the ability of the PS to control frequency

The ability of the system to adapt to the variations of supply and demand is called *flexibility*. Downward flexibility is its ability to cope with increasing frequency (through production reduction or consumption increase, see Figure 1). Upward flexibility is its ability to regulate decreasing frequency (through increasing production or decreasing consumption). These frequency variations can be expected (e.g., expected increase of demand, or of production) or unexpected (Véronique Beillan, Caroline Bono, Sophie Bouly De Lesdain, & Fabien Bricault, 2018).

[2] Faults are short-circuits and insulation faults

[3] In alternative current (AC) power systems, electricity parameters oscillate at a given frequency, reflecting the frequency at which spinning machines producing, and consuming electricity, spin

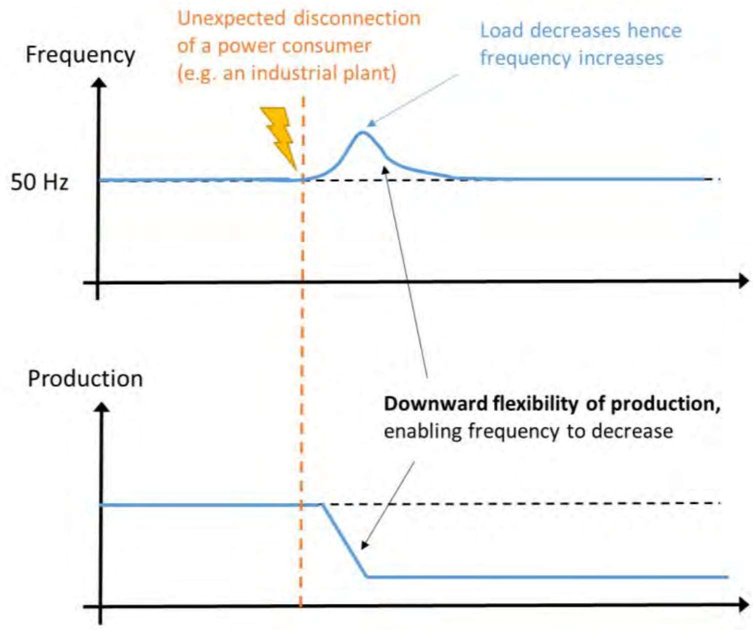


Figure 1: Illustration of downward flexibility lever activation following the disconnection of an important load (for example and industrial plant being disconnected). Source: The Shift Project.

Flexibility has two components (Véronique Beillan et al., 2018):

- flexibility needs: the need for flexibility comes from the uncontrollable variations of power demand or supply: consumption variations, RES variability, loss of production units or load disconnection.
- flexibility levers: they are the controllable variations of power demand and supply: controllable production units (flexible thermal – fossil fuel and nuclear – units, controllable RES), load management, storage and destocking, or call of the previous levers through interconnections. The grid, market design and operational processes must enable these levers to perform their flexibility roles.

In this section, we talk about flexibility assuming that total capacity is enough to meet demand. We only consider the dynamics of the supply to follow demand.

The verification of total capacity is considered in section about structural demand-supply balance (LTT)

Flexibility must be considered at different forecast horizons, depending on when it will potentially be needed. If flexibility is needed right away, only a few levers can be activated fast enough to fulfill the need. The further away in the future one looks, the more levers can be activated (some levers can be activated in a few minutes, other in tens of minutes, or hours…). However, flexibility needs evolve in the same direction: the further away in the future one looks, the more uncertainties there are about production and consumption, hence the more flexibility is needed in case these uncertainties materialize. As a result, flexibility is studied at different forecast horizons in order to make sure levers will always be available to cover uncertainties (Véronique Beillan et al., 2018).

C. A flexibility need for each forecast horizon

Flexibility needs can be categorized as follows, depending on their forecast horizon (Véronique Beillan et al., 2018):

- Inertia: this is the first response of the system to frequency variation. This response is due to its "natural" tendency to resist frequency change (see section on inertia below). The PS needs a high enough inertia in order for frequency not to change too fast in case an unexpected event happens.
- Reserves: reserves are an automatic or manual action at the production or load level in order to restore frequency stability and frequency value in a timely fashion, in case an imbalance happens. There is a need for a fast enough reaction time in order to counter frequency variation, and a need for enough capacity to restore frequency value.
- Daily flexibility (day-ahead or infra-day): this is the need for preparing a day-ahead plan for production, ensuring in a fine way that supply and demand will effectively match on the subsequent day, on an hour-to-hour basis. In most future studies, the term *flexibility* is used for infra-day flexibility.
- Weekly flexibility to season horizon flexibility: this is the need for preparing a rough production plan at the week to season scale.

- Constraints management for the grid (transmission and distribution): this is the need to plan several years ahead for the infrastructures and control devices that will enable to fulfill the future flexibility needs. These aspects are handled in section about long-term transition of power system.

D. Several kinds of levers to fulfill these needs

In order to fulfill these needs, flexibility levers exist. They can be gathered in four categories (Véronique Beillan et al., 2018):

- Conventional power generators: for fast action (a few minutes), they can modify the power they deliver, in an upward or downward direction if their operating point is not already at its highest or lowest and if they are already started. For slower action (tens of minutes for hydropower and a few hours for thermal power generators), conventional generators can be started or stopped. Thermal generators currently fulfill most of the flexibility needs. Some technological evolutions in nuclear power and in natural gas turbines could enable an increase of their flexibility.
- Load management and demand response within the industry sector, tertiary sector, or housing sector: this kind of flexible load is already able to provide flexibility services (reserves acting on the load side). Load management gathers three levers:
    - load shedding: consumer decides to cancel its consumption for a short time. This decision can be locally compensated by the use of another source of energy (for example a fuel engine-generator).
    - load delay: load is automatically delayed (such as for French storage water heaters)
    - demand turn up: consumers are asked to turn up their consumption. This service is asked in case of extreme downward flexibility needs.

  Load management capacity depends on market rules and regulations which determine the interest a consumer has to accept a management of her consumption. The development of load management depends on its competitiveness against other means to ensure grid constraint management and on the evolution of technologies enabling load management.
  Demand response is based on the behavior of consumers in reaction to live price signals. The ability of consumers to react to price signals depends on the information they have about their consumption and the prices. Hence with proper incentives, price signals can be organized such as to provide flexibility services.
- Storage devices, in particular hydro power (traditional or pumped-storage) or electrochemical storage (batteries), can provide flexibility services. Storage can provide downward flexibility (by storing up energy) and upward flexibility (by injecting electricity). The different flexibility services it can provide depend on the type of storage through its key characteristics: energy capacity and power capacity, as well as swear patterns. Storage can also participate in grid constraint management. However, electrochemical storage is not economically competitive yet compared to a solution based on RESV curtailment (ensuring downward flexibility at low cost) and CCGT (ensuring upward flexibility at low cost, even with a carbon price). This situation depends on the market design and the revenues for different flexibility services. EVs, as storage devices, can participate in flexibility services.
  Similarly, P2X technologies[4] can participate in flexibility services.
- Variable Renewable Energy Sources (VRES, composed of photovoltaic systems (PV) and wind turbines): they could provide flexibility services with proper adaptation of their inverters (see below). However their variability limits their ability to do so and requires good forecasting capabilities. RESV curtailment is a downward flexibility which should be taken into account when designing the PS, as an alternative to grid reinforcement (grid constraint management).

E. Different markets for infra-day to season forecast horizons

The day-ahead market is the mechanism through which electricity bulk prices are set for each hour of the day ahead. This market gathers electricity producers and electricity bulk buyers. It sets the day-ahead production plan of electricity producers taking into account the inertias of the different elements of the PS.

[4] P2X is the set of processes converting electricity in another potential energy which can be stored: power to heat, power to gas, power to fuel, power to products or power to liquids (Véronique Beillan, Caroline Bono, Sophie Bouly De Lesdain, & Fabien Bricault, 2018)

Closer to real time is the infra-day market. This market enables buyers to modify their positions given contingencies which appeared since their latest day-ahead position.

Further away from real time is the futures market. Futures market enable actors to buy or sell energy for a given future period of time, with a price fixed in advance (Véronique Beillan et al., 2018).

Longer-term flexibility (at the scale of several years) is ensured by studies leading to proper investments in flexibility levers. Such studies can be led if proper incentives to do so are in place (for example, a proper market design should give incentives to invest in flexibility levers if flexibility needs increase) (Véronique Beillan et al., 2018).

F. Inertia and reserves are key for flexibility real-time management

1. Inertia: the physical tendency of the PS to resist to frequency changes

Inertia is a technical term that describes the ability of a power system to resist changes in frequency.

Inertia is an inherent property or characteristic of each generator and element of load that is on-line and *coupled directly* (as opposed to electronically coupled) to the interconnection. The inertia of the PS is the sum of the combined inertias of all the connected generators and loads (Eto, Undrill, Roberts, Mackin, & Ellis, 2018).

Conventional synchronous generators (or Synchronous Machines, SMs), as well as rotating load devices include a turbine system and rotating components exhibiting mechanical inertia, and as such they are capable of storing kinetic energy in this rotating mass. Because that energy can be extracted from or absorbed into these rotating masses during system disturbances, an interconnected system of machines is able to withstand fluctuations in net load and generation. For example, reducing the speed of a nuclear plant 1.6 GW alternator from 1500rpm to 1470rpm requires the same amount of energy as stopping 22 40-tons trucks running at 100km/h[5] (Véronique Beillan et al., 2018).

Load significantly participates in inertia. As a consequence, if load evolves to more electronically coupled engines instead of directly coupled motors, PS inertia will decrease[6] (Eto et al., 2018).

2. Reserves: the controlled reaction of the PS to counter frequency changes

The main close-to-real-time flexibility capacities of the system are called reserves. Their objective is to handle strong balance variations which are not forecasted by day-ahead or infra-day plans (for example subsequently to faults on production units, forecast mistakes, variations of RES production or of consumption, or several at the same time, see section on reliability).

Reserves are composed of:

- Frequency Containment Reserve (FCR, ENTSO-E naming), or primary reserve, automatically triggering action in participating plants (or consumers) within a few seconds. Its goal is to restore the production-consumption balance, stabilize the frequency and limit its fall (or rise). In the European power system, the upward FCR must represent 3 000 MW, which corresponds to the power of the two biggest power units.
  In case inertia is not high enough, a very fast reaction to frequency variation should be automatically triggered (within a second or so) at production or load level. This emerging need is called Fast Frequency Containment Reserve (Fast FCR)[7].

[5] Inertia in the European PS is between 20 and 30 mHz/s (this frequency variation rate is called rate of change of frequency). In other words, if a synchronous generator is suddenly disconnected, the global frequency of the PS does not decrease faster than 30 mHz/s. (Véronique Beillan et al., 2018)

[6] Directly coupled motors "slow down" when frequency declines and reduce power consumption, and thereby work in concert with FCR delivered by generators. By not slowing down and not reducing power consumption, electronically coupled motors no longer contribute or support FCR delivered by generators.

[7] A few PSs are already calling for larger Fast FCR, such as the PJM network in the North East of the US or National Grid UK

- Automatic Frequency Restoration Reserve (aFRR), or secondary reserve, enabling to restore the frequency to 50 Hz and the exchanges through interconnections
- Manual Frequency Restoration Reserve (mFRR) and Replacement Reserves (RR), or tertiary reserve. They are manually activated in order to replace the preceding reserves and get back to the initial reserve situation. (Véronique Beillan et al., 2018)

A key moment in the control is when FCR takes over when frequency starts to drop. The speed at which it must react depends on the system inertia: the lower the inertia, the faster the FCR must be in order for frequency not to drop too low[8] (Eto et al., 2018).

If frequency drops too low, rolling blackouts[9] are triggered. If frequency changes too fast or spikes too high, many equipment of the power system are automatically disconnected, which might lead to blackouts. (Véronique Beillan et al., 2018)

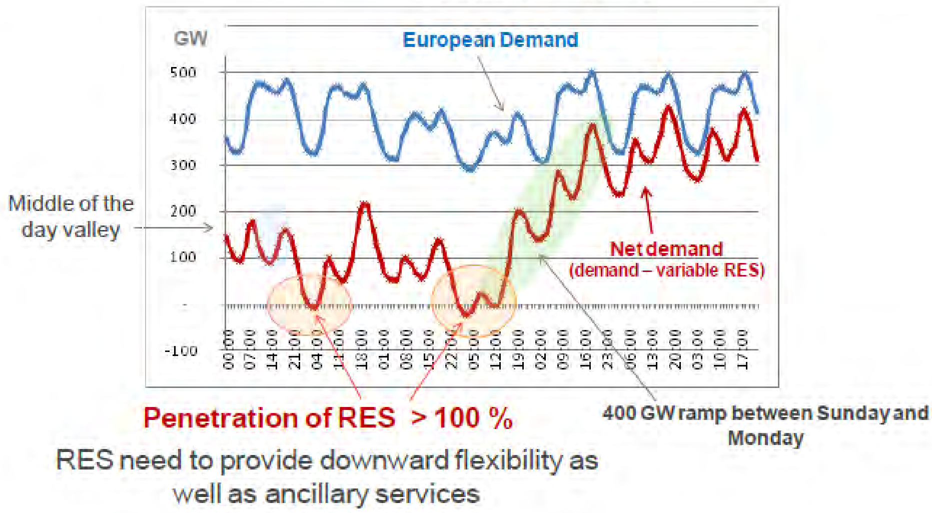
G. Greater shares of VRES impact flexibility needs at several forecast **horizons…**

The evolution of PSs in scenarios may lead to issues about flexibility needs. These issues have emerged through the observation of lowly interconnected power systems with rising shares of VRES, such as the Irish (Eirgrid) or Texan (ERCOT) ones.

For scenarios implementing a growing share of VRES, flexibility needs evolutions can be expected. Simulations of the European PS with a 60 % share of RES run by EDF led to the following conclusions (EDF, 2015):

- VRES variability impacts season to infra-day horizons flexibility needs.
    - At day to infra-day horizon, the greater the VRES share, the shorter the duration of flexibility needs, but the greater their magnitudes. Also, with more VRES, the more often they will produce in excess, hence the more often downward flexibility will be required (see Figure below, source (EDF, 2015)).

FIGURE 10 : LOAD-GENERATION BALANCING BECOMES QUITE COMPLEX FOR PERIODS WITH HIGH NET DEMAND VARIABILITY



    - At season horizon, the more VRES, the more inter-season flexibility will be required. Indeed, in Europe VRES tend to produce in excess in spring and summer but produce too little in winter.

The larger the geographical perimeter of the PS, the lower the variability of production at global scale (aggregation effect). Wind and PV generation present an intermittent generation profile at site level but as a result of natural geographical diversity this intermittency can be reduced when total production is

[8] The key factors determining the lowest value of frequency in case of a frequency drop are (a) the effective inertia constant of the system, which determines the initial rate of decline of frequency; and (b) the rate at which generation is increased by FCR response

[9] Intentionally engineered electrical power shutdown where electricity delivery is stopped for non-overlapping periods of time over different parts of the distribution region

considered at regional or national level. However, wind regimes are often somewhat correlated across Europe. Thus at the European system level a significant variability in the output of wind generation as a function of atmospheric conditions is observed. Conclusions are similar for PV (EDF, 2015).

- VRES uncertainty impacts reserves needs. VRES rely on weather-related energy. The more VRES in the PS, the more the production relies on weather events, hence the greater the uncertainty about production. This uncertainty is reduced when weather forecast accuracy is improved. It is also reduced when the geographical perimeter of the PS is larger. Indeed chances are low that uncertainties of local productions all materialize as forecast mistakes at the same time and in the same direction. In other words, local uncertainties taken together in one interconnected PS do not add up.
- Inertia decreases with more power electronics inverter connected plants, as VRES. Nowadays the spin of a wind turbine is disconnected from the frequency it injects on the grid through the inverter, in order to optimize its power production (Véronique Beillan et al., 2018). By nature, PV power is not produced through a spinning machine and is connected through inverters (BMZ Deutsche GIZ GmbH, 2013; Kroposki et al., 2017). Inertia issues appeared on ERCOT power system in Texas (Matevosyan, 2017) and on Eirgrid in Ireland (O'Sullivan, Power, & Kumar, 2013), leading to curtailing VRES production in order to ensure a minimal level of inertia.

A decrease in inertia may be counterbalanced by a faster FCR. Hence a need for faster FCR could appear in scenarios with a high share of VRES (Véronique Beillan et al., 2018).

H. **… But** can also partly constitute, and benefit from, new flexibility levers

As flexibility needs may evolve in some scenarios, new flexibility levers can be introduced in order to fulfill these needs. Here is a review of the different technologies which could be used as flexibility levers.

1. Inertia can be provided by synchronous machines and by synchronous compensators whereas VRES and batteries can provide fast FCR

A first, conventional solution to tackle the insertion of more VRES is to ensure there is always enough inertia in the system, at each moment in time, by keeping a minimal amount of Synchronous Machines. However, this could lead to maintaining high-emissions, or high-costs plants running or to VRES curtailment.

A low-cost option to maintain inertia is to install synchronous compensators (see Figure 2), which are synchronous machines running without producing electricity. They are useful to bring their inertia to the system (Véronique Beillan et al., 2018). They can provide all the ancillary services of conventional generators except those requiring active power, i.e. they can provide fault current, inertia and voltage support (see following sections) just like a synchronous generator. (Brown et al., 2018)

Figure 2: a synchronous compensator at Templestowe substation, Melbourne Victoria, Australia (source: Wikimedia Commons)

Another lever to help power systems with decreasing inertia is to connect VRES through Virtual Synchronous Machines (VSM) inverters (grid-forming). In these inverters, a set of algorithms enable it to mimic the physics and control laws of Synchronous Machines (SMs) in terms of stability (Véronique Beillan et al., 2018)

With VSM connections, wind turbines can contribute to fast FCR for a limited amount of time (about 5-10 seconds), by suddenly reducing rotor's speed and transforming the corresponding kinetic energy into electric energy[10] (Eto et al., 2018). However, this requires that wind turbines be producing when the need for inertia appears.

Similarly, electric batteries can provide such a response when batteries are not empty (Kroposki et al., 2017).

Technically though, the response of VRES with VSM inverters is very fast FCR rather than inertia (see next section): if total inertia from Synchronous Machines becomes very low, VSM responses can become too slow in case of frequency variation, leading to PS instability (Véronique Beillan et al., 2018).

Furthermore, economically speaking, headroom should be allocated to conventional power plants because variable costs of wind and solar are virtually zero.

If it happens that wind and solar penetration levels become extremely high additional storage devices could be installed, only for the purpose of providing active power capacity to the system for inertia simulation and for reserves (BMZ Deutsche GIZ GmbH, 2013).

2. Faster FCR is cost-efficiently provided by batteries, and by VRES curtailment for downward FCR

Faster FCR can be provided by several means: storage (batteries, inertial storage…), VRES, load… However nowadays batteries seem to be the most cost-competitive solution, as illustrated by the solutions proposed for a 200 MW fast FCR call by National Grid UK: out of 64 proposals, 61 were for batteries.

As previously developed, PV and wind turbines can easily provide fast FCR when production must be decreased, by electronically curtailing production. They can also provide fast FCR when production must be increased, if they keep some headroom and if the event happens when they produce. In other words, they have to be permanently and significantly curtailed to provide this service (Véronique Beillan et al., 2018). Here again, for economic reasons, this service could be more efficiently provided by extra storage devices (BMZ Deutsche GIZ GmbH, 2013).

Thus VRES controllers, if carefully designed and under the previous conditions, can provide primary response that is faster to the response from conventional generators because of the fast-response speed from the power electronics interfaces (Kroposki et al., 2017).

[10] This fast FCR capability is sometimes improperly referred as "synthetic inertia"

I. A challenge for future studies: properly estimating flexibility balance with large shares of VRES

As developed above, modeling challenges arise for scenarios implementing large shares of VRES, as they largely modify flexibility needs and also partly constitute levers. We reviewed how future studies tackle this challenge as of today.

1. Future studies consider season to infra-day flexibilities, but simpler methods cannot properly represent the effects of large shares of VRES

Most future studies we reviewed ensure that season to infra-day flexibility needs are fulfilled by flexibility levers. Two main methods are used to do so:

- The computationally lighter method is to define a few "time-slices" within the year and simulate what happens in these time slices (IRENA, 2017). They usually are one-, or two-hour slices representative of the different load and generation patterns within the year. Typically, slices represent a day for each season in order to account for load variation with seasons. Assumedly, if the power system correctly operates over these time slices, it does so at any time. This method is particularly efficient for modeling power systems whose operation can be finely represented by a little number of exemplary conditions. The more variable generation in the power mix, the greater the number of different conditions it undergoes, hence the less adapted this method. In order to check the balance between load and production, an estimate of VRES production is produced. This estimate is based on a *capacity credit* which is allocated to the different VRES technologies. This credit represents an average capacity (over the installed pool of the considered technology) modelled as guaranteed for different types of loads (baseload, mid-load, peakload...). For example, a model can allocate a peakload capacity credit of 10 % for wind turbines, meaning that 10 % of the installed capacity is considered as available at peakload time. Then dispatchable production is computed. This method is used by POLES model (Keramidas, Kitous, Schmitz, European Commission, & Joint Research Centre, 2017), PRIMES model (E3Modelling, 2018), and was used by the WEM before 2016 (International Energy Agency, 2018).
- The previous method can be improved so as to represent and simulate load and supply for all the one-hour time slices of each year. In other words, this method uses an hourly time step (that is, 8760 one-hour time-slices). It better represents variable renewable power generation, as it simulates a greater diversity of weather patterns. Many studies we reviewed use this method (ADEME, 2012; Association négaWatt, 2014; ECF, 2010; Fraunhofer ISE, 2015; NégaWatt, 2017; OECD/IEA, 2017). Some studies go further and simulate several years of weather pattern for each state of the power system during its transition. This allows to further test the robustness of the power system to different weather patterns, especially to rare and extreme ones. The weather data can be the exact reproduction of measured weather data in past years (such as in (ADEME, 2015; ADEME / Artelys, 2018; Agora Energiewende, IDDRI, 2018)), or it can be simulated to stochastically generate realistic weather data (as is performed in (RTE, 2017)). In the latter case, weather data including climate change effects can be simulated.

2. A few future studies consider reserves, very few properly represent the effects of large shares of VRES

Some future studies take into considerations reserve needs and reserve levers in their modeling, checking the balance between them. Traditionally, in power systems based on dispatchable units, ensuring a given amount of reserve margin (that is, extra capacity which would be available above peak load) was enough to tackle the largest uncertainty (which was estimated using the worst realistic fault which could occur). The difficulty for models implementing large shares of VRES is to model the uncertainty of VRES production, which leads to greater reserve requirements.

Only a few models perform such uncertainty estimation (such as METIS model by ARTELYS (ARTELYS / European Commission, 2016; ARTELYS / European Commission, 2017) or the Dynamic System Investment Model from Imperial College (ECF, 2010; Imperial College London, NERA, DNV GL, 2014)). They do so by modeling VRES expected production and actual production, hence modeling for each hour of the year the gap between "forecasted" VRES production and "obtained" VRES production. One method is to simulate "forecasted" production by using databases of historically forecasted weather and deducing from them what the production forecast was at that time. Another method is to stochastically generate the "actual" production, hence modeling the weather uncertainty.

3. The few future studies considering inertia do so **"manually"** (without modeling it)

Inertia is rarely considered in future studies. In the cases it is considered, the amount of synchronous production is evaluated at each hour of the simulation (hence only models using an hourly time-step can perform it), and compared to exogenous thresholds. A static threshold can be used (e.g. ENTSO-E claims that 150 GW of spinning production must be operating at any time within the Wester Europe power system in order to ensure an appropriate minimal level of inertia), as is done in (RTE, 2017). Alternatively, a dynamic power threshold can be used in order to take into account the fact that power load level varies with time (indeed, for low loads the static threshold might be oversized). The ratio of non-synchronous generation over total generation ("System Non-Synchronous Penetration") is computed at any time and must not get above a fixed threshold. For example, Eirgrid, the Irish Transmission System Operator accepts 65 % of System Non-Synchronous Penetration (ADEME / Artelys, 2018).

However, the inertia of load (that is, inertia of spinning devices which consume the electricity) has to be considered: simulations showed that the lower the load, the greater the required amount of system synchronous penetration (EDF, 2015). Inertia of the load is not considered in the future studies we reviewed. This may lead to biased estimates of inertia requirements. E.g. too loose dynamic thresholds may be used for low load levels. In addition, load could significantly evolve during the transition, affecting inertia requirements: if load evolves to more electronically coupled engines instead of directly coupled motors, PS inertia will decrease[11] (Eto et al., 2018).

J. A summary of flexibility levers and the needs they can fulfill

Below is a table summarizing the already available, and potential flexibility levers against the needs they can each fulfill (Véronique Beillan et al., 2018). Storage technologies, hydropower, dispatchable biomass, as well as thermal production and flexible consumption can fulfill both upward and downward flexibility needs as long as no saturation effect applies (for example, some storage energy capacity might be empty, some thermal power units might already be operating at its highest point, or no flexible consumption offer is available at a given time). VRES with Virtual Synchronous Machines inverters (VSMs) can provide downward flexibility through curtailment, and upward flexibility only if they operate with headroom. In both cases, they must be producing power to be flexibility levers. Furthermore, as primary, secondary and tertiary reserves need to be sustained for a given amount of time before replacement reserves restore them, the associated flexibility levers must be sustained for several minutes, which may not be the case of VRES production.

[11] Directly coupled motors "slow down" when frequency declines and reduce power consumption, and thereby work in concert with FCR delivered by generators. By not slowing down and not reducing power consumption, electronically coupled motors no longer contribute or support FCR delivered by generators.

<table>
<tr><th></th><th colspan="7">System needs</th><th>Grid needs</th></tr>
<tr><th></th><th>Season flexibility</th><th>Week flexibility</th><th>Day / infra-day flexibility</th><th>mFRR + RR</th><th>aFRR + FCR</th><th>Fast FCR</th><th>Inertia</th><th>Grid constraints</th></tr>
<tr><td rowspan="4">Storage</td><td></td><td></td><td colspan="4">Batteries</td><td></td><td>Batteries</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td colspan="2">Fly wheels</td><td></td></tr>
<tr><td></td><td colspan="7">Pumped hydro</td></tr>
<tr><td></td><td></td><td colspan="3">Compressed air</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Thermal production</td><td colspan="5">Thermal power (nuclear and flame)</td><td></td><td>Thermal power</td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="2">Engine generator</td><td></td><td></td><td>Engine generator</td></tr>
<tr><td rowspan="5">RES</td><td colspan="2">Large hydropower</td><td colspan="5">Hydropower</td><td>Small hydropower</td></tr>
<tr><td></td><td></td><td colspan="4">Wind farms (with VSM)</td><td></td><td>Wind farms</td></tr>
<tr><td></td><td></td><td colspan="4">PV farms (with VSM)</td><td></td><td>Small PV</td></tr>
<tr><td></td><td></td><td colspan="6">Concentrated solar power</td></tr>
<tr><td></td><td></td><td colspan="6">Dispatchable biomass</td></tr>
<tr><td rowspan="5">Flexible consumption</td><td></td><td></td><td colspan="4">Evs (load management and V2G with VSM)</td><td></td><td>Evs</td></tr>
<tr><td></td><td></td><td colspan="2">Smart appliances</td><td></td><td></td><td></td><td>Smart appliances</td></tr>
<tr><td></td><td></td><td colspan="3">Cold/ heat in housing and tertiary</td><td></td><td></td><td>Cold/ heat in housing and tertiary</td></tr>
<tr><td></td><td></td><td colspan="3">Industrial load management</td><td></td><td></td><td>Indust. load management</td></tr>
<tr><td>Power2X (Gas, liquids, H2…)</td><td></td><td colspan="3">Power2X (gas, heat…)</td><td></td><td></td><td>Power2X (gas, heat…)</td></tr>
<tr><td rowspan="2">Flexibility devices</td><td></td><td></td><td></td><td></td><td></td><td></td><td>Synchronous compensator</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>Rotating load</td><td></td></tr>
</table>

Figure 3: already available, and potential flexibility levers against the needs they can each fulfill (Véronique Beillan et al., 2018). Reading key: Storage technologies can provide different services of flexibility. For instance, fly wheels can provide fast FCR and inertia.

K. The larger the PS, the lower the flexibility needs

At all forecast horizons, increasing the geographical perimeter of the PS in addition to ensuring a proper centralized control of flexibility levers leads to a reduction in flexibility needs through aggregation effect. (Véronique Beillan et al., 2018)

L. Are smart grid technologies flexibility levers?

New smartgrid technologies, such as new grid forecast management solutions[12], advanced control functions and smart meters represent opportunities to manage flexibility needs at global and local scales. However, a local management of flexibility needs could lead to a suboptimal global management. The effects of local management of flexibility is still under study. In all cases, local management requires a close partnership between TSOs and DSOs (Véronique Beillan et al., 2018).

Recommendations on dynamic demand/supply balance

A scenario strategy about frequency management and flexibility should be defined and justified. It should include considerations on the decision to study dynamic demand/supply balance or not. This strategy depends on the Planning Question and on the study overall strategy.

If the strategy is to discard this aspect, a qualitative analysis of the limitations it induces in the study should be performed.

The different aspects of flexibility which are considered should be reported, and their link to the study strategy should be outlined.

[12] Forecast and simulation tools based on a closer monitoring of distribution grid enabling to avoid reinforcement works and to optimize production (ENEDIS, 2016)

Hereunder are aspects of flexibility which may be reported about. These aspects are impacted by the overall structure of the PS and the level at which frequency is controlled (local level/ national level/ continent level…).

Questions in italic are examples to illustrate the aspects which are dealt with.

- Considered categories (forecast horizons) of flexibility needs should be made transparent. *For example: What forecast horizons are considered in the scenario for evaluating the balance between needs and offer? In what respect is it useful to consider these horizons and not others with regards to the study strategy?*
- Considerations on the coverage of the flexibility needs by the levers during the tested years, and on the indicators to convey this information, such as: is the obtained lever mix sufficient to cover the considered needs? If not, what are the impacts? These considerations should be provided for all the forecast horizons which are considered in the scenario. *For example: over the set of considered test years, are the needs fulfilled by the proposed levers' mix? If not, how often is the mix insufficient? What are the impacts of the insufficiencies on public perception, on economic criteria…? What would be the main trade-offs to consider to get a better coverage in the scenario?*
- Overall methodology used to assess the level of demand and supply balance for the different forecast horizons which are considered in the study. For example, a methodology to assess inertia level is proposed in (Krakowski, 2018).

The following aspects may be detailed for a greater level of transparency. Dealing with those aspects should not require extra core work if the previous aspects have been presented. However, they require extra work for popularization and final editing.

- Time pattern of levers' activations through the year and for each considered forecast horizon; activation mechanisms if they significantly differ from current ones. *For example: When, and how much, is the wind production curtailed? When do wind turbines participate in upward flexibility?*
    - In particular, day-ahead to infra-day activation patterns are sometimes extensively described in scenarios (hour-per-hour description of power production and consumption, including storage pattern). A strategy about day-ahead activation patterns should be explicited.
      The following aspects could be described: Load, power generation, storage (consumption and production), demand-response and load management.
      Those aspects can be described per technology (or another disaggregation level depending on the driving questions), per region (or another resolution depending on the driving questions), and/or per type of actor. For example, demand-response activation could be described per type of actor (industry, households…).
      Other indicators could be provided, such as loss indicators (*how much loss, including curtailment, for each tested year?*); full load equivalent operating hours for production units, transmission load factor for relevant lines, or power import/export indicators.
- Available flexibility levers with regards to the technological storyline, for each considered forecast horizon. *For example: What levers are considered in the scenario (batteries, thermal power units…)? In the scenario time frame, when does each of them start to be available? Is it consistent with the technological storyline?*
- Characteristics of flexibility levers, such as operating constraints (ramp up and ramp down capabilities, minimal or maximal operating points…), their costs, their impacts on society, how society adopts them (acceptance), or the environment, etc. *For example, depending on the study strategy: what are the characteristics of batteries with regard to flexibility (energy capacity, power, life duration as a function of use…)? How much lithium is required for the production of one battery?*
- Evolution of these characteristics through the scenario. The origin of these evolutions: technological (for conventional generators, storage devices and VRES) and / or behavioral (for load management and demand response). *For example: Do cost, technical characteristics and resource consumption of batteries evolve through the scenario? If yes, what does explain these evolutions?*

- Flexibility markets, for different forecast horizons. *For example: What are the considered market incentives for developing flexibility levers in the scenario? Are there any evolution of the flexibility market in the scenario?*
- Flexibility needs evolution through the scenario, such as: the total capacity for each considered forecast horizon, the frequency at which the need appears, the emergence of new flexibility needs. These needs depend on the weather-dependent share of production and on weather forecast performances. *For example: What evolution of the need for inertia during the scenario timeframe? Does a need for Fast FCR appear during the scenario timeframe? What evolution of the need for reserves? What evolution of the frequency of call of reserves?*
- Evolution of flexibility levers capacities per type of lever; geographical locations of the levers. *What evolution of the number of PV farms with VSM inverters in the scenario? What evolution of the installed capacity of such farms? Where are these farms located?*

M. Greater shares of inverter-connected plants lead to lower quality electrical waves

For the AC to DC transformation, inverters used to connect PV and wind turbines to the grid produce electrical waves which are not perfect 50 Hz sine waves. Instead they contain some upper frequency waves, in the 0 kHz to 2 kHz range (harmonics) when produced by older inverters. These harmonics can disrupt the operation of some devices and accelerate the aging of electrical insulants.

New inverters use faster mechanisms hence they produce different, but still imperfect sine waves containing higher frequency waves (greater than 2 kHz). Furthermore, each inverter emits different types of waves depending on its operating point and on the local voltage at its connection with the grid. The effects of those waves are the same as harmonics if their magnitude is too high.

These waves can be damped by installing filters, which induces extra-costs.

However, their variety and complexity make simulation and forecast studies about them difficult. More research is needed to evaluate the extra-costs of damping as necessary these waves (Véronique Beillan et al., 2018).

Recommendations on sine waves quality

A scenario strategy about sine wave quality should be defined and justified. It should include considerations on the decision to study this subject or not. If the strategy is to discard this aspect, a qualitative analysis of the limitations it induces in the study should be performed.

This strategy depends on the Planning Question and on the study overall strategy. The different aspects of it which are considered should be reported, and their link to the study strategy should be outlined.

The following aspects may be reported about:

- Evolution of the quality of the sine wave through scenario timeframe
- Overall methodology to assess this quality
- Impacts and induced costs if sine wave quality is inadequate

The following aspects may be detailed for a greater level of transparency. Dealing with those aspects should not require extra core work if the previous aspects have been presented. However, they require extra work for popularization and final editing.

- Evolution of the level of harmonics emissions, determined by the amount and type of power electronics devices connected to the grid
- Evolution of the level of damping, determined by the quantity of installed damping filters, and associated costs

III. Voltage control

A. Voltage: a decentralized parameter which must be controlled locally

Voltage is the parameter in a power system that indicates whether there is a reactive power[13] imbalance in an area of a system (BMZ Deutsche GIZ GmbH, 2013).

Voltage is maintained around different values with different confidence intervals for the transmission grid and the distribution grid. Indeed the functions of these networks are different: the transmission grid must reduce losses and preserve stability (requiring high voltages); the distribution grid must finely tune the voltage for the end-consumer so that all her equipment operates (requiring a tight confidence interval on voltage) (Véronique Beillan et al., 2018).

Voltage evolves through time following supply and demand variations as well as grid topology variations. At a given time, voltage evolves through space as a function of the topology of the connected equipment and plants (RTE, 2004). Space evolution reflects reactive power production and consumption. Lines consume reactive power, hence reactive power decreases with the distance to its source.

Voltage should be maintained around its nominal value at all points of the system.

Equipment connected to the grid as well as power plants require the voltage to be maintained around its nominal value. Indeed these equipment are designed to operate for contractual voltages. Equipment can be worn or damaged if it is too high. If it is too low, intensity can become too high for lines. Low voltage can induce transformers and power plants malfunctions as well as making the operation of the grid more difficult (RTE, 2004).

A low voltage problem can lead to a system-wide collapse, for example several minutes or hours after a big power plant has unexpectedly disconnected (BMZ Deutsche GIZ GmbH, 2013).

Finally, voltage control is required to control power imports and exports through interconnections.

B. Current voltage control: several organs organized in a complex architecture distributed over the grid

Voltage stability can be decomposed within two components:

- Static voltage stability is the maintenance of local reactive power balance during normal operation of the system.
- Dynamic voltage stability is the ability of the system to absorb disturbances. This ability is mostly driven by the short circuit current delivered during a disturbance. This topic is developed in Section about short-circuit current. The current section is about static voltage stability only.

Reactive power decreases with travelled distance. Hence it is more efficient to correct voltage variations very close to consuming devices (that is, at the level of distribution grid). However, control at the transmission grid level is required as it provides the frame within which the distribution grid operates. Control capabilities are also installed at the interface between the two grids through tap changers[14], and then in the distribution grid through passive devices (capacitors).

At the transport grid level, conventional generation plants provide a voltage control capability, each up to a certain point. Hence they are a simple and efficient lever for voltage control. In Europe, this service is remunerated through contracts with TSOs, or is regulated by law in order to get connection clearance (Julia Merino, Inés Gómez,

[13] Reactive power is not a power per say. It is expressed in volt-ampere reactive (var). It appears in electrical components containing capacitors or self-inductance, as they produce a phase gap between the voltage wave and the current wave. In these cases, a part of the current creates a magnetic field which is not used for mechanical work but leads to extra losses and reduction in voltage (Véronique Beillan et al., 2018).

[14] Device controlling the transformation ratio of the transformer to control voltage when load varies.

Elena Turienzo, & Carlos Madina, 2016). These plants should be smartly located on the grid in order to ensure an efficient control everywhere (RTE, 2004). However, in case they do not provide enough reactive power, other reactive power compensation means exist:

- Synchronous compensators, which are equipment providing a similar reactive power control as synchronous machines (see Frequency stability section)
- Other pieces of equipment such as capacitors, self-inductances, Static VAR Compensators (providing the same services as synchronous compensators but with a static, power electronics technology) and tap changers in transformers. These equipment are controlled by TSOs (and DSOs at the distribution grid level) (Brown et al., 2018; Véronique Beillan et al., 2018).

Static VAR Compensators, synchronous machines and compensators can provide a fast control, which cannot be provided by capacitors, self-inductances or tap changers. Hence the latter means are used in priority for slower control needs in order to keep enough fast control margin.

Synchronous machines (conventional power plants) and synchronous compensators provide voltage control services. They provide three different control mechanisms depending on the considered time horizon and geographical perimeter:

- Primary control is a local, automated and instant control. It regulates the voltage at terminals of alternators' stators.
- Secondary control is automated. It coordinates the actions of the alternators of a given region and regulates voltage at strategical points on the grid. This control acts at a one-minute time scale.
- Tertiary control is not automated. It coordinates voltages across regions and enables plants participating in the primary and secondary controls to keep control margins, by starting other plants or modifying the operating points of some plants.

At the distribution grid level, consumers have incentives to install capacitors to compensate for reactive power losses. These incentives might not be sufficient. Hence some passive voltage control equipment are installed on the distribution grid. They are automatically controlled by DSOs.

Voltage is regulated on the transmission grid in priority, and then on the distribution grid. Indeed, a stable transmission grid avoids system-wide voltage collapses. This is why voltage regulators act faster on the transmission grid than on the distribution grid.

C. Voltage control in power systems with high share of inverter based VRES: a near-term engineering challenge but a low priority consideration for long-term planning

Inverter connected RES can provide reactive power if the inverter is properly designed (IRENA, 2017) but this certainly affects their ability to provide active power (Kroposki et al., 2017). This inverter technology is already being offered by manufacturers (Brown et al., 2018; IRENA, 2017).

With such inverters, wind and PV generators have reactive power control capabilities, only as long as they produce power (BMZ Deutsche GIZ GmbH, 2013). However, for the same installed capacity inverter-connected plants can deliver lower levels of instant reactive power than SMs.

Batteries could also provide such services (IRENA, 2017).

But the integration of VRES can still have negative impact on voltage stability:

- Reactive power cannot be transferred over long distances but must be made available locally. However, especially wind farms are very often located in remote areas (remote from load centers). For this reason, even if wind farms are able to deliver reactive power, it may not be made available at the location where it is actually needed.

- The connection of generation plants to the distribution grid (also known as decentralized, or embedded generation, for example small scale RES) requires adaptations of the voltage control system (Heard, Brook, Wigley, & Bradshaw, 2017; IRENA, 2017). Indeed, voltage control has originally been designed for centralized power systems[15]. Hence if more power production is connected to distribution grid, transmission grid will have to adapt its control mechanisms (Véronique Beillan et al., 2018).

However, these issues can typically be mitigated at moderate costs by installing additional reactive power compensation where needed, either based on switched capacitor banks (mechanical switched capacitors / MSCs) or static var compensators (SVCs). These technologies are readily available. Such adjustments are not expected to significantly alter the long-term transition path. The required dynamic performance of the additional reactive power sources must be identified by dynamic simulations looking at near-term, local voltage stability aspects and transient stability aspects. (BMZ Deutsche GIZ GmbH, 2013; IRENA, 2017; Brown et al., 2018)

The impact of VRE generators on voltage control, therefore, may be assigned a low priority in planning long-term transition. The details of the voltage control design will be tackled on a near-term basis. The associated costs are likely to be low compared to power capacity costs (IRENA, 2017).

Some optimizations of the distribution grid might be possible too, such as a coordinated control of transformers, or local voltage control on the low-voltage transmission grid (ENEDIS, 2016).

Recommendations on voltage control

A scenario strategy about voltage stability should be defined and justified. It should include considerations on the decision to study voltage stability or not.

If the strategy is to discard this aspect, a qualitative analysis of the limitations it induces in the study should be performed.

The different aspects which are considered should be reported, and their links to the study strategy should be outlined.

Hereunder are aspects of voltage stability which may be reported about. These aspects are impacted by the overall structure of the PS. Questions in italic are examples to illustrate the aspects which are dealt with.

- Voltage control operating results
- Overall methodology to assess those results
- Impacts and induced costs if voltage control is inadequate

In more details, here are aspects which may be considered to properly answer the previous points:

- Evolution of the architecture of the voltage control system with regard to the evolution of the capacity mix (especially the share of power production connected to the distribution grid). *Does the architecture switches from a step-down concept to a new one?*
- Equipment participating in the voltage control, depending on the speed (primary / secondary + tertiary) of the control: evolution of the available technologies with regard to the technological storyline. *Are new voltage control technologies available?*
- Evolution of the stock of equipment, drivers of this evolution, potential associated costs. *How many MSCs, SVCs, synchronous compensators, batteries, VRES units are installed during the scenario? Are there markets or regulations fostering this evolution? What are the associated costs? How much material does it consume to produce them?*
- Voltage control mechanisms (if they are significantly different from the current ones), voltage control operating results and potential impacts of these results. *Does the resulting voltage control system manage to keep voltage stable for normal operation of the PS? During disturbances? What interactions with society and the economy if it does not?*

[15] Typical voltage control concepts are strictly based on a step-down concept, where step-down transformers regulate the voltage of the next lower voltage level, which means that reactive power balancing is only possible in the direction from higher to lower voltage levels (BMZ Deutsche GIZ GmbH, 2013)

IV. Rotor angle stability

A. What is rotor angle stability and why is it important?

Rotor angle stability is the state in which the power system (PS) is when all the alternators of plants run at the same electrical speed. This common speed is the *frequency* of the PS.

PS stability is possible thanks to an elastic link called "synchronizing torque" acting through electric variables and synchronizing the generators between them.

When the synchronizing torque is broken (for example in case of a long short-circuit event), generators can start running at different speeds. PS frequency has no meaning anymore. The electric wave at each point of the grid is the compound of waves of different frequencies: voltage and intensity beats appear, which produces unacceptable constraints on connected equipments: overintensities, overvoltages… The power system is not stable anymore. (RTE, 2004)

Two contingencies can lead to a rotor angle instability:

- An undamped oscillatory perturbation (oscillatory stability)
- A critical fault lasting for too long (transient stability) (BMZ Deutsche GIZ GmbH, 2013)

The grid is instable by nature. Hence SM are designed to maintain their own stability and the global PS stability, through the tuning of their controllers: these controllers ensure that oscillatory perturbations are damped and that the SM stays synchronized in case of a critical fault. Modeling and testing are performed before the commissioning of SMs (Véronique Beillan et al., 2018).

However, especially in the lower frequency domain, in which inter-area oscillations are relevant, it is not possible to fully attenuate power oscillations with the above described mitigation measures. Here, power oscillation dampers (PODs) can be applied on the transmission network, which modulate the voltage for improving system damping through the voltage dependence of loads. (BMZ Deutsche GIZ GmbH, 2013)

Going from a synchronous machines (SM) based power systems (PS) to an inverter-based PS has implications on rotor angle stability.

B. Managing oscillatory stability in PSs with a high share of VRES requires next-generation "grid-forming" inverters

The current PS, dominated by synchronous machines, can be represented by a set of masses (machines) linked by springs (the grid). When a perturbation comes, a mass can come to oscillate, which naturally leads the other masses to oscillate. The whole system can react and filter this perturbation as the controller of each plant is properly tuned. (Véronique Beillan et al., 2018)

Because oscillatory stability is a small disturbance phenomenon, it is a system property being independent from the type of disturbance. Hence, in the case that an undamped type of perturbation exists, even the smallest of them will get excited, leading to a loss of synchronism. (BMZ Deutsche GIZ GmbH, 2013)

If synchronous machines are replaced with power electronics converters, then these converters must be set to be robust to the perturbation as opposed to follow and reproduce it (such as current "grid-following inverters") (Kroposki et al., 2017).

Grid-forming inverters can be used in order for them to be robust to perturbation and to contribute themselves to the rotor angle stability. They are also called Virtual Synchronous Machines (VSM). (Kroposki et al., 2017; Véronique Beillan et al., 2018)

This next-generation, grid forming inverters will be able to operate in low-inertia grids without a stiff frequency (that is, with a very low amount of SM's); however, this requires to increase the inverter current rating, hence its cost (Brown et al., 2018), possibly up to very high costs (Véronique Beillan et al., 2018).

C. Managing transient stability in high VRES share PS: general and specific studies must be led

Transient stability describes the ability of a power system to maintain in synchronism following large disturbances, such as grid faults. Because of the nonlinear nature of power systems, transient stability depends not only on system properties but also on the type of disturbance. Because of the complexity of the problem, transient stability can only be analyzed by a series of time domain simulations using dynamic models of generators, governors and controllers.

Generally, the impact of wind and solar generators on transient stability can be positive or negative, depending on each specific situation (their location, local topography of the grid). The impact of VRES must be studied in each individual case. (BMZ Deutsche GIZ GmbH, 2013)

Studies must be led to estimate the potential impacts of a decreased inertia and short-circuit power on the transient stability with the increased share of inverter connected plants. (Véronique Beillan et al., 2018)

Recommendations to scenario producers on rotor angle stability

A scenario strategy about oscillatory stability and transient stability should be defined and justified. It should include considerations on the decision to include them in the scenario or not. This choice depends on the Planning Question and on the study overall strategy. The different aspects of rotor angle stability which are considered should be reported, and their link to the study strategy should be outlined.

The following aspects of rotor angle stability may be reported about:

- The technologies used to ensure rotor angle stability, their evolutions through the scenario (in terms of maturity and commercial availability, costs, efficiency…). If these evolutions are deemed uncertain, sensitivity analyses may be proposed.
- The equipment installed on the PS and the PS organization; the drivers of PS evolutions.
- For transient stability assessment, which requires very specific studies, simplified assessment methods, or modeling strategies may be proposed

V. Other ancillary services

A. Short circuit current

1. Short-circuit current: an image of the power sources in opposition to a fault

Short circuit current is the current which is measured in case of the worst short-circuit fault[16]. It is composed of the currents coming from the sources which are in opposition to the fault.

Different types of power sources contribute differently to fault opposition. A Synchronous Machine can oppose perturbations by injecting up to 6 times its current rating. Inverter-connected VRES can contribute between 1.1 to 1.6 times their current ratings, due to the physical characteristics of interrupters composing the inverter.

(Kroposki et al., 2017; Véronique Beillan et al., 2018)

2. Evolutions in short-circuit current can require evolutions of the fault detection system

Fault detection systems on the grid are based on local current monitoring. If current reaches a given threshold, then a fault is detected, triggering corrective action. Hence a lowering of short-circuit current could lead to potential missed fault detections, which could endanger people and equipment (Véronique Beillan et al., 2018). For scenarios based on inverter connected generators, a lower amount of short circuit current would be available, leading to such risks.

On the other hand, more connections at the distribution grid level may lead scenarios to propose stronger links between the distribution grid and the transmission grid, bringing more short circuit current from the transmission grid to the distribution grid. (Julia Merino et al., 2016)

Also, the connection per say of a power generator (through an inverter or not) to the distribution grid might disturb the fault detection system. The protection system is designed for centralized PS (on-way flows). Hence, for a power plant being connected at distribution grid level, detection devices which would be located at the upstream of the new connection may cause missed detections or false detections (Véronique Beillan et al., 2018).

Another impact of low short-circuit current levels is a difficulty in starting big industrial electrical motors, which consume 6 to 7 times more current when they are being started than when they run.

3. Possible evolutions: adding short circuit current sources, updating fault sensors or making the fault detection system "smart"

For scenarios with more VRES and / or generators connected at the distribution grid level, several technologies can be proposed to conserve the efficiency of the fault detection system in a PS with more VRES:

- Synchronous generators could be installed at relevant locations and bring the missing short-circuit current. However this solution may not be the most economical (Brown et al., 2018)
- Over-current detection could be replaced by differential protection and distance protection, both of which are established technologies (Brown et al., 2018)
- Over-current detection could be updated by adding a flow-direction detection capability (Véronique Beillan et al., 2018)
- The fault detection system could be made "smart" by allowing a communication between all the detection devices. However, this would induce extra costs, cybersecurity concerns and resilience issues. (Véronique Beillan et al., 2018)

[16] This fault is called three phase bolted fault and it consists in a short circuit for the three phases together, as if they were bolted together; this kind of faults leads to the maximum short circuit current values

- The architecture of the protection system could be re-designed and modified taking into account the new connections (and those available technologies). (Véronique Beillan et al., 2018)

Concerning a possible difficulty to start industrial motors (as they consume 6 to 7 times more current when they are being started than when they run), synchronous generators can solve the problem. Another solution would be to equip big motors with electronical speed variators to decrease the starting current, albeit at an extra cost. This would however decrease load inertia which is useful for frequency stability (as mentioned p10).

Recommendations to scenario producers on short circuit current

A scenario strategy about fault detection should be defined and justified. It should include considerations on the decision to study it or not. This strategy depends on the Planning Question and on the study overall strategy. The different aspects of fault detection which are considered should be reported, and their link to the study strategy should be outlined.

The following aspects may be reported about:

- Evolution of the fault detection system: installed technologies and/or new architecture of the fault detection system; drivers of this evolution.
- Smartization of the fault detection system, in line with technological storyline; associated costs and potential impacts on PS resilience (especially in case of a greater coupling with the IT system)
- Evolution of the fault detection system efficiency: new risks of false, or missed detections; impacts of these risks.

B. Fault ride-through capability

Fault-ride through (FRT) is the capability of electric generators to stay connected in short periods of lower electric network voltage (voltage dip) until the faulted element has been cleared from the transmission system. The fault-ride through capability mostly depends on the reactive power control (which determines the necessary time to clear a fault) (Julia Merino et al., 2016).

In the case that a substantial amount of wind or solar generators will be connected that do not have the FRT capability, a single line fault in the transmission grid (which is a frequently occurring event) can potentially lead to the disconnection of a large amount of generation and hence might increase the amount of generation that can be lost because of a single fault. In such a case, FCR would react to stabilize frequency. Hence capacity reserve would have to be designed with the amount of generation not equipped with FRT capability.

However, because FRT-capability is a standard feature of modern wind and PV-inverters, all wind and PV-generators in a system can easily be equipped with FRT-capability for ensuring frequency stability. (BMZ Deutsche GIZ GmbH, 2013)

Recommendations to scenario producers on fault ride-through

Scenario reports should define and justify their strategy about FRT capability. The strategy should include considerations on the decision to study this capability or not, in line with the Planning Question and study strategy. The different aspects of FRT capability which are studied should be reported and linked to the overall study strategy.

The following aspects may be reported about:

- Evolution of the capacity share which is equipped with the FRT capability, by generation technology
- The potential impacts of this evolution on system reliability, costs.

C. Black-start capability

1. Black start: the ability to restart the electricity system in the case of a total blackout

Black start is the ability to restart the electricity system in the case of a total blackout. Most thermal power stations consume electricity when starting up (e.g. powering pumps, fans and other auxiliary equipment), so special provisions are needed when black-starting the system, by making sure there are generators which can start without an electricity supply.

Typically system operators use hydroelectric plants (which can generate as soon as the sluice gate is opened), diesel generators or battery systems, which can then start a gas turbine, which can then start other power plants (for example). (Brown et al., 2018)

This ability to restart a grid is critical to overall system reliability. To accomplish this, the generation on the system needs to be able to both act as a voltage source and provide adequate power to start electrical equipment with high in-rush currents, such as transformers and motors. (Kroposki et al., 2017)

2. Black start capability: a near-term issue for high VRES mixes; still under research for very high shares of VRES

Storage devices as well as VRES could participate in black starting the PS in times when they can provide energy, because they do not need power to start (Brown et al., 2018). However, the amount of current they can provide, which is lower for inverter-based VRES than for conventional power plants, must be sufficient to restart the thermal power plant equipment. The required amount of current depends on the topology of the grid (Kroposki et al., 2017).

Battery storage systems have been shown to be able to black-start gas turbines (Brown et al., 2018).

In any case, conventional solutions can still be used (hydropower, diesel generators). However, as long as the amount of generation and load is not sufficient, PS stability is very weak. During this phase, the variability of VRES could trigger protection devices, leading to a failed restart. As mentioned above, fault detection system must be adapted to high shares of VRES.

For scenarios with an inverter-dominated PS, black start must include a beat leader giving the frequency on which all other power plants can "connect". Indeed, the usual frequency beat provided by regulated conventional power plant (synchronous machines) can become too weak to efficiently operate. This question is still under research. (Véronique Beillan et al., 2018)

Recommendations to scenario producers on black start capability

A scenario strategy about black start management should be defined and justified. It should include considerations on the decision to study it or not. This strategy depends on the Planning Question and on the study overall strategy. The different aspects of black starting which are considered should be reported, and their link to the study strategy should be outlined.

Here are some of the aspects which may be studied:

- Black starting ability: equipment participating in this service, potential associated costs, evolution of the ability in the scenario time frame, potential impacts of a longer black starting time
- Beat leader presence especially with very high shares of inverter connected generators: equipment ensuring it within the scenario time frame, potential associated costs

VI. Planning for market designs and regulations: a near-term challenge but a low priority for long-term planning

Markets or regulations explain the incentives of agents to provide electricity, all the ancillary services and future ancillary services.

For each scenario, depending on the specificities of their markets and regulations, the changes in their PS may require market design, or regulations, evolutions. New ancillary needs might appear and should be remunerated in order for economical agents to propose ancillary services fulfilling them.

For example, the integration of VRES in UK and Ireland led those countries to alter their reserve market design in order to add slow ramp up and ramp down products. They also added a product for Fast FCR, and Irish market remunerates inertia.

In Denmark, markets have been created for short-circuit power and for reactive power. (Véronique Beillan et al., 2018)

In scenarios with high shares of VRES, power and ancillary services markets will have key issues to tackle:

- They should coordinate together in order to find the right market design for each of them. Indeed many technologies will participate in several markets at the same time (for example, synchronous compensators could participate in voltage control, in short-circuit power and in inertia at the same time). They should also coordinate with markets for other energies interacting with electricity (for example the heat network could participate in flexibility services by replacing electricity demand at the right time).
- They should answer the question of their geographical scale (local / regional / European markets), and of the interactions between different scales.
- As ancillary services might be more distributed, and especially coming more from distribution grid (where most VRES are connected), the questions of the interaction between GRT and GRD, and of the responsibility to ensure reliability, should be addressed. (Véronique Beillan et al., 2018)

However, the way markets are organized can be changed in a matter of a few years, at low cost. The mere question of planning market designs is not a priority for long-term planning, compared to the planning of physical devices composing, and structure of, the PS ensuring its proper operation.

Considerations on markets are included in the different recommendation sections as aspects that some scenarios may want to describe.

Bibliography

ADEME. (2012). *L'exercice de prospective de l'ADEME - « Vision 2030-2050 »*.

ADEME. (2015). *Un mix électrique 100% renouvelable ? Analyses et optimisations*.

ADEME / Artelys. (2018). *Trajectoires d'évolution du mix électrique 2020-2060 - Synthèse*.

Agora Energiewende, IDDRI. (2018). *L'Energiewende et la transition énergétique à l'horizon 2030*.

ARTELYS / European Commission. (2016). *METIS Technical Note T2 - METIS Power Market Models* (p. 53).

ARTELYS / European Commission. (2017). *METIS Technical Note T6 - METIS Power SYstem Module* (p. 43).

Association négaWatt. (2014). *Scénario négaWatt 2011-2050 - Hypothèses et méthode*.

BMZ Deutsche GIZ GmbH. (2013). *Analysis of System Stability in Developing and Emerging Countries* (p. 43).

Brown, T. W., Bischof-Niemz, T., Blok, K., Breyer, C., Lund, H., & Mathiesen, B. V. (2018). Response to « Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems ». *Renewable and Sustainable Energy Reviews*, *92*, 834-847. https://doi.org/10.1016/j.rser.2018.04.113

E3Modelling. (2018). *PRIMES MODEL VERSION 2018 - Detailed model description* (p. 221).

ECF. (2010). *Roadmap 2050 - A Practical Guide to a Posperous, Low-Carbon Europe*.

EDF. (2015). *Technical and economic analysis of the European electricity system with 60% RES*.

ENEDIS. (2016). *Programme 2016 de R&D et d'Innovation d'Enedis* (p. 32).

Eto, J. H., Undrill, J., Roberts, C., Mackin, P., & Ellis, J. (2018). *Frequency Control Requirements for Reliable Interconnection Frequency Response*. 116.

Fraunhofer ISE. (2015). *What will the energy transformation cost? - Pathways for transforming the German energy system by 2050*.

Heard, B. P., Brook, B. W., Wigley, T. M. L., & Bradshaw, C. J. A. (2017). Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems. *Renewable and Sustainable Energy Reviews*, *76*, 1122-1133. https://doi.org/10.1016/j.rser.2017.03.114

Imperial College London, NERA, DNV GL. (2014). *Integration of Renewable Energy in Europe* (Nº 9011-700).

International Energy Agency. (2018). *World Energy Model Documentation - 2018 Version* (p. 82).

IRENA. (2017). *Planning for the Renewable Future - Long-term Modelling and Tools to Expand Variable Renewable Power in Emerging Economies*.

Julia Merino, Inés Gómez, Elena Turienzo, & Carlos Madina. (2016). *Ancillary service provision by RES and DSM connected at distribution level in the future power system D1.1* (p. 175). SmartNet.

Keramidas, K., Kitous, A., Schmitz, A., European Commission, & Joint Research Centre. (2017). *POLES-JRC model documentation.*

Krakowski, V. (2018). *Intégration du renouvelable et stratégie de déploiement du réseau électrique: réconciliation d'échelles spatio-temporelles dans des exercices prospectifs de long terme*.

Kroposki, B., Johnson, B., Zhang, Y., Gevorgian, V., Denholm, P., Hodge, B.-M., & Hannegan, B. (2017). Achieving a 100% Renewable Grid: Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy. *IEEE Power and Energy Magazine*, *15*(2), 61-73. https://doi.org/10.1109/MPE.2016.2637122

Matevosyan, J. (2017). *ERCOT Renewable Integration*. Consulté à l'adresse https://www.ethz.ch/content/dam/ethz/special-interest/itet/institute-eeh/power-systems-dam/documents/Seminar/Integrating%20renewables%20into%20Texas%20grid.PDF

NégaWatt. (2017). *Scénario négaWatt 2017-2050*.

OECD/IEA. (2017). *World Energy Outlook 2017* (p. 782).

O'Sullivan, J., Power, M., & Kumar, S. (2013). *The Impact of Non-Syncrhnous Generation on System Inertia*. Présenté à Dublin. Consulté à l'adresse http://cigreireland.ie/wp-content/uploads/2013/08/Session-2-The-Impact-of-Non-Synchronous-Generation-on-System-Inertia.pdf

RTE. (2004). *Mémento de la dûreté du système électrique*. TIempo Editions.

RTE. (2017). *Bilan prévisionnel de l'équilibre offre-demande d'électricité en France*.

Véronique Beillan, Caroline Bono, Sophie Bouly De Lesdain, & Fabien Bricault. (2018). *Les systèmes électriques de demain - Un défi pour la transition énergétique*. Tec & Doc Lavoisier.

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The Shift Project, a non-profit organization, is a French think-tank dedicated to informing and influencing the debate on energy transition in Europe. The Shift Project is supported by European companies that want to make the energy transition their strategic priority & by French public funding.

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Transition desirability in energy transition scenarios

Technical file #9 – Draft version

Information and recommendations for scenario producers

This document is part of a set of 12 technical files. These files have been produced by *The Shift Project* after one year and a half of research and experts consultations on the different aspects of energy transition and the future studies around these aspects.

Our project, "Power Systems 2050 – Guidelines for design," started in January 2018, with the participation of 10 experts who defined the key subjects which according to them have to be collectively tackled by future studies about the power transition. *The Shift Project* then investigated each of these subjects, consulting in total 40 experts, organizing 4 workshops, and reviewing a large bibliography, including a dozen of future studies about power (and energy) transition at different geographical scales.

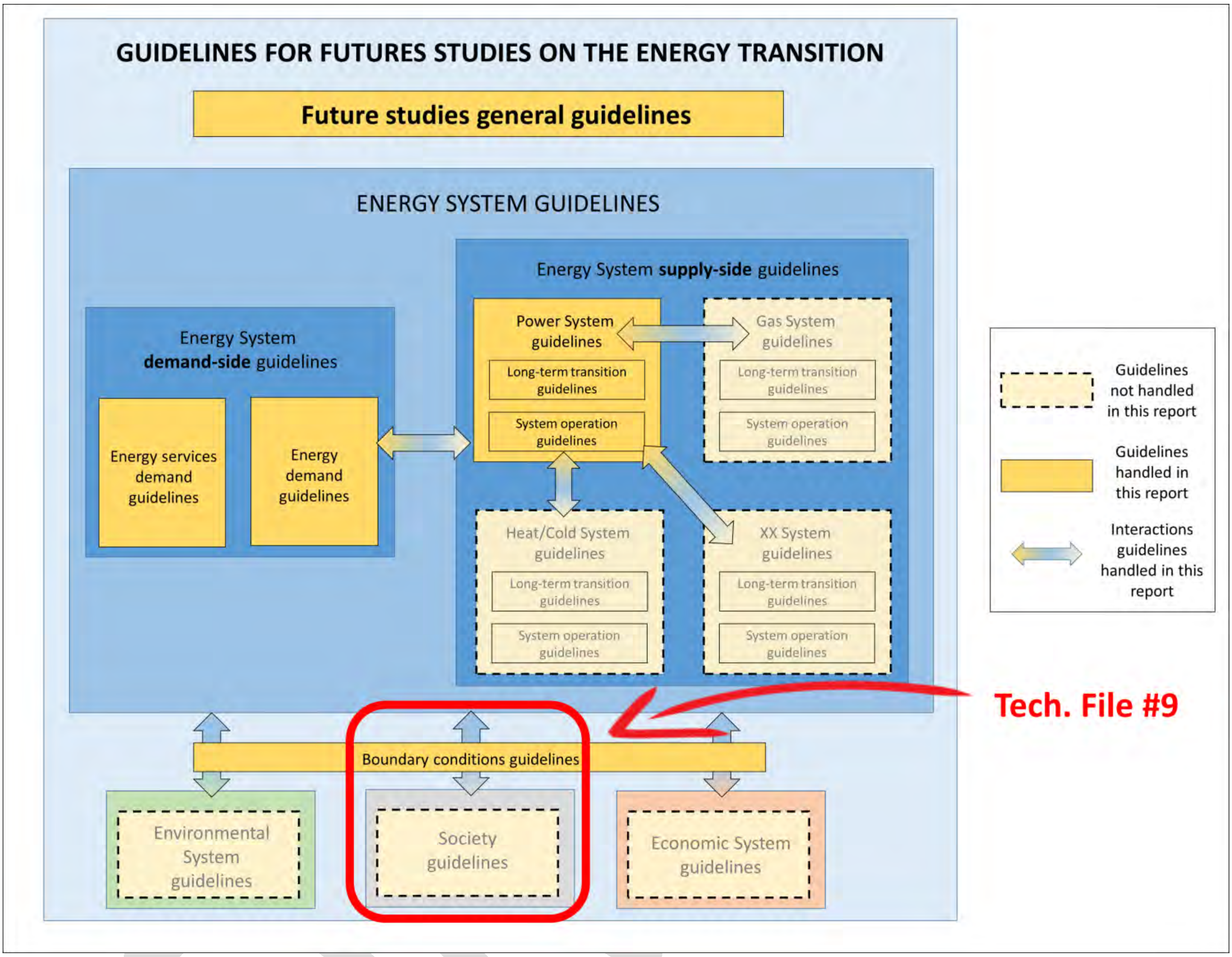
The goal of this project is to produce a set of guidelines addressed to scenario producers. These guidelines seek to foster transparency and consistency *within* future studies and to develop a common language *across* studies. By defining a number of important items which are key to deal with in future studies, we actually propose a study template which enables a better understanding of the location of each proposed scenario on the tree of possible transitions. Once again, the objective is not to *rank* studies, or scenarios, but rather to *compare* them to get a better collective overview of the different aspects of the transition (what are the differences between studies in terms of driving questions, hypotheses, models, methodology, results?).

Several aspects of the energy transition are handled in these technical files. However, on the energy supply-side only the power system has been studied. The main reason for this choice is that we had to start from somewhere with limited resources, and the power system seemed to be a key system to study in the energy transition context, towards a low-carbon economy, as shown by the growing number of future studies focusing on this system. However, the guidelines we propose could be completed by analyzes on the other energy supply-side systems (the gas system, oil system, heat system and so on).

Each technical file tackles several aspects of future studies for the power (and energy) transition. Here is the complete list of the technical files produced during the project:

#	**Technical file title**
1	Future studies on the energy transition
2	Energy transition models
3	Boundary conditions for energy transition scenarios
4	Long-term evolution of energy consumption in energy transition scenarios
5	Lifestyles and consumption behaviors in energy transition scenarios
6	Long-term evolution of the power system supply-side in energy transition scenarios
7	Power system operation in energy transition scenarios
8	Impact assessment in energy transition scenarios
9	Transition desirability in energy transition scenarios
10	Environmental assessment of energy transition scenarios
11	Economic evaluation of energy transition scenarios
12	Employment assessment of energy transition scenarios

Altogether, these files cover the fields described on the following map of the guidelines for future studies on the energy transition. The document you are reading covers the red-circled topics.



In addition to these technical files, three complementary notes have been produced as specific focuses on the following aspects: material criticality in energy transitions (in French, to be translated and added to technical file #10), levelized cost of electricity (LCOE) in energy transition future studies (in French) and discount rate in energy transition future studies (in French).

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Table of content

Reading keys

Explanation box, containing key information for a better overall understanding of the subjects.

Recommendations to scenario producers:

These boxes contain the recommendations for scenario producers.

The word "should" means that scenario producers, if they are to follow the guidelines, must substantiate the corresponding point. The words "may" or "might" relates to suggestions, ideas to help the scenario producer respond to the point.

Questions in italic are examples of questions scenario producers might ask to substantiate the points. They are here in an illustration purpose.

Phrases in italic relate to words which are being defined and will be subsequently used in the framework.

Phrases which are highlighted in yellow refer to other technical documents of this series.

I. Transition desirability

Desirability of the transition refers to the fact that the transition is desirable for the different actors composing a society. In case a transition seems not desirable by some actors, they can raise acceptance questions and generate conflict with the transition planner(s).

By better understanding why such conflicts emerge in the real world, scenario producers can better take desirability and acceptability considerations into account in their scenarios.

A. Transition projects may lead to four types of conflicts between the general public and projects holders

Literature on acceptance is large as far as installation of technology infrastructure is concerned. However, for our energy transition subject, this concept is extended to the desirability of a complete transition.

(ADEME, 2011) proposes a frame which describes the different types of conflicts which may arise when a project is implemented. These conflicts express different types of oppositions from individuals to a project taking place within a transition.

- The *uncertainty conflict* emerges when opponents are afraid of the potential impacts of the projects on themselves, their local environment, their jobs and their ways of lives (as inhabitants of a territory and workers in a given sector).
- The *substantial conflict* emerges when opponents contest the nature of the proposed project in general (as citizens), such as a proposed global policy in case of a public project.
- The *structural conflict* emerges when the proposed project comes from an illegitimate actor, that is, an actor which is considered as not representing the general interest.
- The *procedure conflict* emerges when opponents contest the way of leading the project, typically when transparency on the project is not ensured or when dialogue with stakeholders is poor. In this document, we instead consider that good concertation procedures prevent from the other types of conflicts to happen by raising the associated risks beforehand.

Such conflicts are observed in real-life situations for transition projects, such as the installation of wind turbines or the installation of new high-voltage power lines.

As mentioned in the lifestyle section, social aspects are largely neglected in scenarios whereas transitions proposed may encounter great hurdles in the real world because of people possible reluctance towards these transitions or the way they are led.

Acceptance studies often focus on causes of uncertainty conflicts. These causes do not fully explain acceptance behaviors, hence some authors interpret it as volatile, as if partly irrational (Bertsch, Hall, Weinhardt, & Fichtner, 2016). Taking into account the other types of conflicts may improve the overall understanding on acceptance.

(Schubert, Thuß, & Möst, 2015) focuses on the acceptance of an energy transition. According to them, three main aspects should be considered in assessing the acceptance, or desirability, of an energy transition:

- Economic aspect, such as the evolution of costs for different actors, wealth redistribution, employment
- Security of supply for the different actors
- Environmental compatibility and technology risks

These aspects fit in the conflict frame proposed above.

Other stakeholders than individuals can trigger conflicts: corporations can pressurize governments towards reducing as most as possible the possible transition burdens they could bear, such as sunk costs. More generally, who bears the burden of sunk costs is a key question for transition desirability.

The next sections are based on the 4 different types of conflicts proposed by (ADEME, 2011), covering the three main aspects presented by (Schubert et al., 2015). The final section is dedicated to considerations on sunk costs.

Recommendations to scenario producers

Scenario producers should take acceptance aspects into account, as a way to prove the social desirability or to highlight the conflict risks associated with the proposed transition. Hence these risks can be better treated in scenarios. As a consequence scenario producers can explain why and how conflicts risks are negligible in their scenarios. The different types of conflicts this document handles should be considered while building scenarios.

B. *Uncertainty conflicts* are caused by the impacts of changes on individuals

Uncertainty conflict is sometimes described as the NIMBY ("Not in my backyard") syndrome. However, some authors argue that this depiction leads to discard the reasons of discontent by judging them as "egoistic" instead of understanding and tackling them (ADEME, 2011). Furthermore, NIMBY syndrome applies to reactions to the installation of new infrastructure, whereas we include in uncertainty conflicts all the impacts of an energy transition at the individual level. For example, uncertainty about one's job within a transition belongs to this type of conflict whereas job issues are not usually included in NIMBY considerations.

1. Energy is a basic need: its supply should be affordable when needed, secure, and of good quality, during the whole transition

The greater public sees energy as a basic need. Indeed energy is explicitly discussed among the general public as a basic need because of its perceived role in ensuring survival, good health, a decent life, and ability to engage in expected patterns of life. This is particularly salient when considering the wellbeing of vulnerable groups (Demski, Thomas, Becker, Evensen, & Pidgeon, 2019).

Access to energy is seen as a basic right that should be guaranteed because people have no choice but to use it. When "there is no choice" energy demand is described as "constrained" (Martin & Gaspard, 2016).

In this regard, access to energy services should be ensured for all groups of people so they can fulfill their needs when they need it. Hence energy services should remain affordable. If energy price increases (for example through a carbon price), the service should remain accessible using less, or another form of, energy, through low-consumption technologies or alternative technologies. In turn, access to these technologies should be ensured in a timely fashion so that basic needs are continuously fulfilled.

As time-of use pricing may result in high prices during peak times, it may lead to render energy unaffordable for some groups in society if they are not able to shift their demand. Smart metering may not be accepted if reassurance that new pricing would **not compromise people's access to energy when they needed it for** essential services is not provided (Demski et al., 2019). In economic words, constrained energy demand is barely elastic to price. Hence, on the short run, a price rise of constrained energy directly leads to a budget decrease for other expenses, as energy consumption does not decrease.

Along the same line of reasoning, energy security of supply is a key criteria for acceptance. Blackouts or power cuts are not accepted anymore in developed countries, neither by households nor by industries. Many of households' basic needs are enabled by power (food conservation, heating[1], cooking). For industries, power cuts prevent from working, which is not accepted especially in case of high unemployment rates. Some of societies basic needs are fulfilled through power: public lighting for individual security, health services, water system amenities and so on, require power to properly operate. The impacts of a lasting blackout in Western countries would be huge in the current state of affairs. To prevent the most catastrophic impacts of a blackout, infrastructure (such as hospitals, some power plants) are equipped with diesel generators or batteries to keep operating for a few days in case of a lasting power outage (Mark Elsberg, 2017). Réseau de Transport d'Electricité (RTE, the French power transmission operator) describes security of supply as a common good (RTE, 2017).

[1] Some rural households in Canada are equipped with individual diesel generators in case the power network undergoes failures during winter.

Similarly, power quality (a stable and neat tension and frequency wave) is an important criterion because it is needed for usual appliances to correctly work. Too low a power quality would be equivalent to a power cut.

Note that these acceptance issues could also be categorized in the substantial conflict category (that is, an opposition to a project for society level reasons), as people declare that lacking energy should not happen to anybody in the society they live in (Demski et al., 2019).

Recommendations to scenario producers

A scenario strategy about access to power uncertainty conflicts should be defined and justified. It should include considerations on the decision to study this subject or not. This choice depends on the Planning Question and on the study overall strategy. In case the subject is studied, the different aspects of it which are considered should be reported.

Considering those aspects may help to detect the situations in which conflicts about access to power could arise in some scenarios.

Hereunder are aspects of access to power uncertainty conflicts which may be reported about:

- Impacts on access to power generated by the transition: several aspects pertaining to access to power have been presented: affordability, time-of-use pricing and demand side management techniques, security of supply and quality of supply. For each of them, scenario producers should consider the following aspects:
- Type of needs which are impacted: needs are characterized as "basic" when the corresponding demand is constrained; in other words, a basic need is one which people have "no choice" but to fulfill it. Scenario producers should take special care when decreasing the fulfillment of such needs. For example, they may substantiate why the described transition is accepted in their scenarios in which such a decrease happens.
- Type of population which is impacted: different populations are differently exposed to the above-mentioned impacts because their needs may be different (e.g., some households may need to commute over long distances). Scenario producers may take into account the specificities of some populations (such as social categories or type of fabric they live in) when assessing the power accessibility impacts in their scenarios.
- Corrective measures or adaptation impacts: scenario producers may propose extra political measures in their scenarios to avoid conflicts risks related to energy access, such as wealth redistribution measures, wavers for specific populations, communication campaigns… Costs and impacts of such measures should be considered. Economic actors which face power accessibility problems may adapt by getting equipped with fuel-powered portable generators, batteries or any other solution. If they face power quality problems, they might adapt by getting equipped with protective devices. Such adaptation behaviors should be considered and their impacts (on total system costs, GHG emissions and so on) taken into account.

For example, such situations should be detected: a global increase of the power share in households', or companies', budgets; a sharp increase of the power share in a given population's budget due to time-of-use pricing; a significantly lower security of supply; a lower quality of supply. In these situations, scenario producers should substantiate how risks of conflicts are kept low. This might involve extra measures, or adaptations by agents. This may imply, in turn, extra costs or consequences, which may be assessed depending on the study strategy.

2. Transition involves work structure changes: impacts on workers should be considered

Fast transitions require fast changes in the structure of the workforce. Workers may have to face unemployment, undergo trainings to acquire new skills. Expertize may become useless, and the associated status disappear.

These situations may not be accepted by people as workers while they would be accepted as inhabitants, or vice versa (Bögel & Upham, 2018).

Recommendations to scenario producers

Scenarios in which workers have to radically change their professional activity or face unemployment should explain what measures they assume to make it acceptable for them.

The costs and impacts of these measures should be taken into account.

3. Transition involves infrastructure changes: impacts on inhabitants should be considered

The distance between places of dwellings and places of power infrastructure construction is key in local acceptance problems (Bertsch et al., 2016). This can be explained by local impacts on human ecology and by impacts on landscapes.

a. Impacts on human ecology

Most energy transitions within scenarios involve power infrastructure changes. These changes may happen close to dwellings and have impacts on individuals. In particular, power plants and power infrastructure or equipment have different local impacts for human life. For example, wind turbines generate noise (including infrasound), shadows, ice shedding (Scherhaufer, Höltinger, Salak, Schauppenlehner, & Schmidt, 2017). Smart meters have been shown to have (psychosomatic) health effects in France. Biogas infrastructure may generate smells. Fossil fuel power plants generate local air pollution, symbolized by smokestacks.

Some infrastructure represent local industrial risks which may lead to conflicts when being installed: nuclear accidents risks, explosion risks for gas installations (such as biogas production plants) (ADEME / OpinionWay, 2017), hydropower dam ruptures and so on.

Rejection may be explained in some cases by the "fear of the unknown". A study about acceptance of power installations in Germany notes that Power-to-gas technology faces a lower acceptability than other power installations and propose that it is because this technology is still largely unknown (Bertsch et al., 2016).

Following the same line of reasoning, people living close to wind turbines, or to a nuclear plant tend to be more positive about these technologies than people who do not. This effect might be explained by a better knowledge, or more simply by a habituation, to the impacts and risks of the technology by people who live close to it, or by the inverse causation: people who think these technologies are not risky may be more willing to live close to them than people who do not.

b. Impacts on landscape

Power plants, especially VRES ones, take space and as such they modify local landscapes for more people than traditional plants.

VRES development may also require high voltage grid reinforcement. Overhead lines modify local landscapes and this is one reason why they are sometimes rejected: 30% of the high-voltage lines planned in the 2012 Ten Years Network Development Plan (TYNDP) of the European Network of Transmission System Operators for Electricity (ENTSO-E) have delays because of acceptance issues (Véronique Beillan, Caroline Bono, Sophie Bouly De Lesdain, & Fabien Bricault, 2018).

As noted by a German study about acceptance of power infrastructure installation (Bertsch et al., 2016), landscape impacts are the main driving factor of local acceptance problems. This is confirmed by other studies showing the importance of landscape modification in acceptance (ADEME / OpinionWay, 2017; Scherhaufer et al., 2017).

This is linked to the concept of place attachment and to what the installed infrastructure represents for this specific place (Bögel & Upham, 2018). Presumably, if the installed infrastructure is seen as an asset for the territory, or is associated with a desirable vision of the future for its inhabitants, or comes from a local initiative benefiting the territory, landscape impact will be judged favorably; on the contrary, if they are perceived as imposed by a centralized actor with no consideration on local interests, landscape impacts may be judged negatively. Hence landscape impact, seen through the lens of place attachment, may be associated – up to a certain point – to the other causes of conflicts, or desirability (such as structure conflicts).

Recommendations to scenario producers

Scenario producers should assess if the infrastructure changes happening in their scenarios could constitute motives for uncertainty conflicts because of human ecology and landscape modifications, depending on their location relative to dwellings and their specific impacts and perceptions within society. If such risks are detected, producers should substantiate why the transition is still desirable in the scenario, for example by compensatory measures (wealth redistribution, communication campaigns…).

C. *Substantial conflicts* emerge when opponents (citizens) contest the nature of the proposed project in general

Conflict may emerge because of the overall policy context of the project being implanted, and/or because of global impacts on society or the environment, no matter if the project is closely located to one's dwelling. This type of conflict is sometimes called the "Not in Anybody's Backyard" syndrome (ADEME, 2011).

1. Transition inducing inconsistencies between policies and society traits may trigger conflicts

Austrian citizens reacting on wind power installation reported in a poll a lack of policy coherence and consistency across territory levels and policy measures. Providing a consistent global vision was deemed important: for example, the development of renewable energy would be seen as more desirable if it goes along the creation of charging stations for electric vehicles or with the refurbishment of street lighting (assumedly, for lowering its consumption) (Scherhaufer et al., 2017).

Individual comfort or discomfort generated by a transition is important (as described in the previous section), but is not enough to explain the emergence of conflicts. The way those discomforts are distributed over the population and economic actors highly matters and should be done with a sense of equity. For example, it is important that companies bear a part of the efforts along with citizens. This also raises the political question of how to accompany those who lose the most. In other words, a global consistent vision should include considerations on equity within society.

More generally, any energy transition policy may have impacts on social inequalities or may differently affect different population categories (owners of polluting cars, dwellers of energy inefficient buildings…), which may lead to acceptance issues raised by the losers in the proposed transition (Martin & Gaspard, 2016).

The overall consistency of the transition should be clear within policies but also within society. For example, as long as driving a car belongs to a particular class and gender culture which is fostered and maintained by manly image through advertisement, the press, and gender interactions, car use cannot be altered significantly (Uzzell & Rathzel, 2010). In other words, if society incentives are not in line with policy incentives, risks of conflicts against policies increase.

Recommendations to scenario producers

Most transformational scenarios assume a global consistency across policies and society incentives. They generally assume the transition they propose is desirable as a whole.

However, these assumptions should be made explicit and substantiated, e.g. by a storyline.

In this effort, scenario producers should consider the following aspects:

- Discomfort / effort distribution across the different economic actors and across the general population, with regard to the local culture and the risks of conflicts due to possible inequities.
- Possible measures to compensate / accompany those who lose the most, as well as the associated costs and consequences.
- Alignment between society incentives and policy incentives: in case behavior trends (also see section on behaviors) are reversed, substantiation of the reversal should be provided. For example, how does the advertisement environment evolve during a significant transition from car to public transportation?

2. Transition inducing global impacts on the environment may trigger conflicts

The environmental cause grows in European countries. For example, in the context of the implementation of a wind turbines project, Austrian stakeholders considered that the impacts on natural protected areas and on species such as birds and bats were important (Scherhaufer et al., 2017).

Hence environmental considerations can be at stake in the substantial conflicts emerging from a project, no matter if the project is installed closely to the respondents to a poll.

In the German case, importing more power from countries with high shares of nuclear and coal-based power generation could lead to acceptance issues. Indeed, such a transition would be inconsistent with the national objectives of phasing out coal and nuclear power (Agora Energiewende, IDDRI, 2018).

Such a transition may generate conflict whereas local impacts are not in Germany.

Hence such topics as climate change, impacts on protected areas and wildlife, nuclear waste generation and nuclear power potential industrial risks, or overuse of the underground (for Carbon Capture and Storage, gas storage, geothermal power production, underground power transmission lines, nuclear waste storage and so on) (Bertsch et al., 2016) may be evoked in substantial conflicts.

Recommendations to scenario producers

Scenario producers should assess if the global impacts on the environment happening in their scenarios could constitute motives for substantial conflicts. If such risks are detected, producers should substantiate why the transition is still desirable in the scenario, for example by compensatory measures (communication campaigns…).

D. *Structural conflicts* emerge when projects are proposed and driven by non-legitimate actors.

1. More conflicts about public or private infrastructure building can be expected in Europe in the future

More than ever in EU countries, policies and public projects are criticized through the lens of legitimacy. Expertize and scientific facts, which used to be trusted and perceived as legitimate, have lost their influencing power through several mechanisms, as illustrated by the French case (Merad & Trump, 2018).

First, the public loses trust in the government's capacity and will to sustain critical services and to represent the general interest, because (a) large range of activities have shifted from the public to the private sectors, (b) government reactions to past events[2] have been poorly framed and poorly understood by the public, leading to distrust towards government experts (c) public value of projects is sometimes not discussed not even delineated, and (d) growing regulatory complexity increasingly prevents public understanding of how the system functions and why it represents common values.

In addition, the corporate world has lost legitimacy to represent the general interest after cases of "doubt manufacturing" (such as in the Tobacco industry case, or climate change topic) in which scientists have been paid to publish 'product-friendly' scientific studies. In addition, such cases shed doubt on the whole scientific fact.

(Merad & Trump, 2018) conclude: "Coupled with a lack of "citizen culture" and a perceived opacity of the governance and management of common and public affairs, industrial lobbying and collusion with politics has introduced distrust in politics that has contaminated the administrative credibility and reliability of various regulatory agencies in France and abroad."

As a result, more and more decisions to create infrastructure projects, which are based upon a mixture of scientific, business and political negotiations are perceived as not based on the civil perception of evidence because decision agents have lost legitimacy to represent the general interest.

No matter the nature and content of the proposed projects constitutive of the transition, an increasing number of conflicts can be expected as a general trend, finding their roots in legitimacy issues.

Recommendations to scenario producers

Scenario producers should make their strategy about legitimacy issues explicit: do their scenarios include considerations on this topic?

If the currently observed trend in loss of legitimacy of traditional project holders (the State and large/medium corporations) is reversed in the scenario, the storyline should explain why.

Otherwise, impacts of the continued loss of legitimacy should be assessed: is the governance of the transition modified and if so, what are the associated costs? Are transition projects modified? Do they cost more? Do they take more time to implement?

2. Transition may involve data management evolutions: impacts on citizens should be considered

Smart grids require more data about local power consumption, especially data about household's consumption. Data are collected by power distribution companies through automated smart meters (less costly than a human meter reader). This may lead to concerns by some people about the use of their data by these companies. This issue may be linked to a lack of legitimacy in the actors supposedly controlling the collected data.

Recommendations for scenario producers

Scenario producers should assess if the personal data management changes happening in their scenarios could constitute motives for uncertainty conflicts. If such risks are detected, producers should substantiate why the transition is still desirable in the scenario, for example by compensatory measures (management of the data by other, more legitimate bodies, communication campaigns…).

[2] "For example, after Chernobyl (1986), the French authorities in charge of radioprotection endorsed a controversial position in the media that radioactive material from the Chernobyl disaster stopped at the French border (implying that no public health consequences would be borne by the French people)." (Merad & Trump, 2018)

E. Project implementation procedures, such as concertation, may help avoiding conflicts

In order to avoid some of the abovementioned conflicts, local concertation procedures can be followed within territories before projects are launched. Such procedures can lead to improvements in the proposed local projects and to time saving in their implementations. For example, fair revenue distribution may be defined to reduce envy and distrust (e.g. between land owners, residential population, project holders) (Scherhaufer et al., 2017).

Some scenarios assess the impacts of such procedures through sensitivity analyses, coined as "low acceptance" scenarios (ADEME, 2015; ADEME / Artelys, 2018). Power mix modifications happen, which impacts the total cost of the system. However, the costs of organizing and running those local concertation procedures are not taken into account.

Recommendations for scenario producers

Energy transition scenarios in which acceptance issues may lead to conflict may propose, as a general tool, concertation procedures between local actors in territories where those risks arise. By doing so, associated costs (linked to the organization and running of the procedure) and possible consequences (such as different choices of infrastructures) should be taken into account[3].

F. Sunk costs derive from transition urgency and may rise desirability issues

Sunk costs is the part of the capital invested in an existing asset that has not been recovered when the asset is closed. Thus, sunk costs appear whenever an asset is closed before its economic lifetime. The asset is said to be "stranded".

Such situations can trigger conflicts depending on who handles the loss.

1. For society, sunk costs reveal an inconsistency between past choices and new objectives

From a society perspective, a power plant going stranded indicates that the decision to build the plant was an economically suboptimal choice. Indeed, it means the shutdown of the plant is now considered as the best decision despite the fact it could have still worked. Sunk costs arise when past choices are no longer compliant with society's current objectives. A typical example is the premature shutdown of a coal power plant due to its high air pollutant and/or GHG emissions, through regulation, market or tax. In such a (still fictional) case, the past decision of building the coal power plant, based on economic criteria, is considered by society as obsolete in light of climate change considerations. Other examples include car ban in some cities. People owning a car in such cities may undergo a strong loss of utility from their cars, because they cannot use it anymore and because it loses monetary value on the market at the same time.

Stranded assets risk is therefore strongly linked to the time horizon choice of a study (see future studies section) and its social objectives. As explained in the corresponding part, a CGDD study (2016) (CGDD, 2016) shows how some choices with short-term vision can enable to efficiently reach short-term objectives but be counterproductive on the long-term. Doing the same optimization with a long-term objective in mind changes their result: in their case, much more energy carrier changes are made to avoid lock-in after the end-date of the optimization. Thus, when using a marginal abatement cost curve, they recommend to choose carefully the time horizon(s).

[3] This recommendation sums up parts of previous recommendations, about the consequences of avoiding the different types of conflicts we presented.

2. Stranded assets burden sharing may rise desirability issues

By definition, risk of stranded assets rises with the rate (speed) of a transition. This is a typical transition risk. Thus, required changes to face 21st century challenges may put many assets in a stranded position. These sunk costs are a serious issue and well known debate, often cited as a key challenge of energy transition. Indeed, someone has to pay for it. It can be the company operating the stranded asset (e.g. a coal power plant being shut down by law), the user of an owned asset (e.g. a car forbidden to access an area), and/or the State (in case a compensation is provided when the asset gets stranded). In any case, it can raise serious desirability issues.

The perceived fairness of the burden sharing is key in its desirability.

Recommendations for scenario producers

Scenario producers should report about their strategies on stranded assets and sunk costs. Substantiation should be provided if the subject is not handled. If the subject is handled, the following aspects on sunk costs may be reported about:

- Total amount of sunk costs in the scenario. From a society point of view it gives the magnitude of acceptability issues arising from sunk costs. This can be reported in the storyline. *Is there any sunk costs in the scenario? Do they represent a large burden for society?*

- Burden sharing of the sunk costs. *Who loses money when an asset gets stranded in the scenario? The owner of the asset? The State?*

- Possible lack of desirability of the proposed transition due to sunk costs. *Regarding the burden sharing choices in the scenario, may the proposed transition feel unacceptable for some stakeholders?*

G. Better integrating desirability issues in scenarios

As previously argued, imposing elements of a transition through coercion might be extremely costly, would it be in terms of surveillance, propaganda and coercion means but also, evidently, in terms of health and social welfare. No scenario to our knowledge assumes such a coercion to accompany the described transition.

When desirability is explicitly considered, it is often seen as highly uncertain, leading to sensitivity analyses rather than being fully integrated in each scenario at the design stage ((ADEME, 2015; ADEME / Artelys, 2018) perform such sensitivity analyses). In the "high acceptance constraint" scenario from (ADEME, 2015), ground PV panels and on-shore wind turbines are constrained in terms of location: the land which is available for their installation is greatly reduced, assuming households would not desire them close to their houses. In (ADEME / Artelys, 2018), the "low acceptability for ground renewables" scenario assumes an extra cost for these technologies. (European Commission, 2011) provides different scenarios which depend on public acceptance of nuclear technology.

(ECF, 2010) sees desirability issues as an uncertainty which can drive up costs significantly if the described scenarios are to be implemented. But the study does not provide any estimate of the impacts if these issues would turn true.

Sometimes though, some technologies are assumed to be unacceptable and as such are excluded from the study. For example, (Agora Energiewende, IDDRI, 2018) considers in all its scenarios that very large on-shore wind turbines will not be installed in France or Germany because of acceptance issues.

Other studies, such as (Association négaWatt, 2014; Association négaWatt, 2017; Greenpeace, 2015) do not accept nuclear power in their transformational scenarios. By doing so, they are not exactly taking into account acceptance issues. Indeed, they do not only assume nuclear will face desirability issues if it is installed: they, as scenario producers, do not accept it. This directly affects the driving questions they seek to answer. "What could be the energy mix without nuclear power?" is one of them.

In all those cases where acceptability is explicitly considered, only uncertainty conflicts due to the building of new infrastructure are considered as a risk.

Recommendations to scenario producers

Here are some recommendations to properly include desirability issues in scenarios.

Conceptually, there are several ways to include desirability issues in scenarios:

- Desirability can be fully included in the study design, either by substantiating that all the transition elements which are implemented pose no desirability issue, or by detecting desirability issues and including in the results the consequences of these desirability issues. The consequences can be valued in terms of cost, CO_2 impacts and so on, depending on the adaptation by the various modeled actors to the transition elements they deem unacceptable. For example, households can get equipped with diesel generators if power security of supply is not ensured, which would lead to extra costs and, possibly[4], to emitting extra CO_2 emissions.
- As already done in some studies, desirability can be seen as highly uncertain and lead to sensitivity analyses. However, in scenarios in which acceptability is assumed to be low, the consequences of these acceptability issues should be described and their impacts assessed.
- Another way to handle the desirability issue is to provide *concrete*[5] assessment of the consequences of the proposed transition. Indeed, scenario producers cannot be fully informed about the possible desirability issues within complex and evolving populations and cultures. Beyond keeping in mind the recommendations presented above, a way to overcome these uncertainties is to be as concrete as possible about the evolution of lifestyles in the proposed scenarios (see section on lifestyles and behaviors). With concrete descriptions, scenario users can discuss the proposed lifestyles, and investigate their desirability. They can then provide feedback to scenario producers and to the rest of the scenario community so that remarks and knowledge be shared.

[4] Depending on the power mix
[5] See section on Future studies

Bibliography

ADEME. (2011). *La concertation en environnement* (p. 63).

ADEME. (2015). *Un mix électrique 100% renouvelable ? Analyses et optimisations*.

ADEME / Artelys. (2018). *Trajectoires d'évolution du mix électrique 2020-2060 - Synthèse*.

ADEME / OpinionWay. (2017). *Les français et l'environnement* (p. 5).

Agora Energiewende, IDDRI. (2018). *L'Energiewende et la transition énergétique à l'horizon 2030*.

Association négaWatt. (2014). *Scénario négaWatt 2011-2050 - Hypothèses et méthode*.

Association négaWatt. (2017). *Scénario négaWatt 2017-2050*.

Bertsch, V., Hall, M., Weinhardt, C., & Fichtner, W. (2016). Public acceptance and preferences related to renewable energy and grid expansion policy: Empirical insights for Germany. *Energy*, *114*, 465-477. https://doi.org/10.1016/j.energy.2016.08.022

Bögel, P. M., & Upham, P. (2018). Role of psychology in sociotechnical transitions studies: Review in relation to consumption and technology acceptance. *Environmental Innovation and Societal Transitions*, *28*, 122-136. https://doi.org/10.1016/j.eist.2018.01.002

CGDD. (2016). *Trajectoires de transition bas carbone en France au moindre coût*.

Demski, C., Thomas, G., Becker, S., Evensen, D., & Pidgeon, N. (2019). Acceptance of energy transitions and policies: Public conceptualisations of energy as a need and basic right in the United Kingdom. *Energy Research & Social Science*, *48*, 33-45. https://doi.org/10.1016/j.erss.2018.09.018

ECF. (2010). *Roadmap 2050 - A Practical Guide to a Posperous, Low-Carbon Europe*.

European Commission. (2011). *Energy Roadmap 2050 - Impact assessment and scenario analysis*.

Greenpeace. (2015). *Energy [R]evolution*.

Mark Elsberg. (2017). *Blackout. Tomorrow will be too late*. Sourcebooks Landmark.

Martin, S., & Gaspard, A. (2016). *Changer les comportements, faire évoluer les pratiques sociales vers plus de durabilité* (p. 181). ADEME.

Merad, M., & Trump, B. D. (2018). The legitimacy principle within French risk public policy. *Science of The Total Environment*, *645*, 1309-1322. https://doi.org/10.1016/j.scitotenv.2018.07.144

RTE. (2017). *Bilan prévisionnel de l'équilibre offre-demande d'électricité en France*.

Scherhaufer, P., Höltinger, S., Salak, B., Schauppenlehner, T., & Schmidt, J. (2017). Patterns of acceptance and non-acceptance within energy landscapes: A case study on wind energy expansion in Austria. *Energy Policy*, *109*, 863-870. https://doi.org/10.1016/j.enpol.2017.05.057

Schubert, D. K. J., Thuß, S., & Möst, D. (2015). Does political and social feasibility matter in energy scenarios? *Energy Research & Social Science*, *7*, 43-54. https://doi.org/10.1016/j.erss.2015.03.003

Uzzell, D., & Rathzel, N. (2010). La contextualisation de la psychologie environnementale: La nécessaire évolution de la psychologie environnementale. In K. Weiss & F. Girandola (Éd.), *Psychology and Sustainable Development (Psychologie et développement durable)* (p. 247-277). Consulté à l'adresse http://epubs.surrey.ac.uk/805014/

Véronique Beillan, Caroline Bono, Sophie Bouly De Lesdain, & Fabien Bricault. (2018). *Les systèmes électriques de demain - Un défi pour la transition énergétique*. Tec & Doc Lavoisier.

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The Shift Project

The Shift Project, a non-profit organization, is a French think-tank dedicated to informing and influencing the debate on energy transition in Europe. The Shift Project is supported by European companies that want to make the energy transition their strategic priority & by French public funding.

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Environmental assessment of energy transition scenarios

Technical file #10 – Draft version

Information and recommendations for scenario producers

This document is part of a set of 12 technical files. These files have been produced by *The Shift Project* after one year and a half of research and experts consultations on the different aspects of energy transition and the future studies around these aspects.

Our project, "Power Systems 2050 – Guidelines for design," started in January 2018, with the participation of 10 experts who defined the key subjects which according to them have to be collectively tackled by future studies about the power transition. *The Shift Project* then investigated each of these subjects, consulting in total 40 experts, organizing 4 workshops, and reviewing a large bibliography, including a dozen of future studies about power (and energy) transition at different geographical scales.

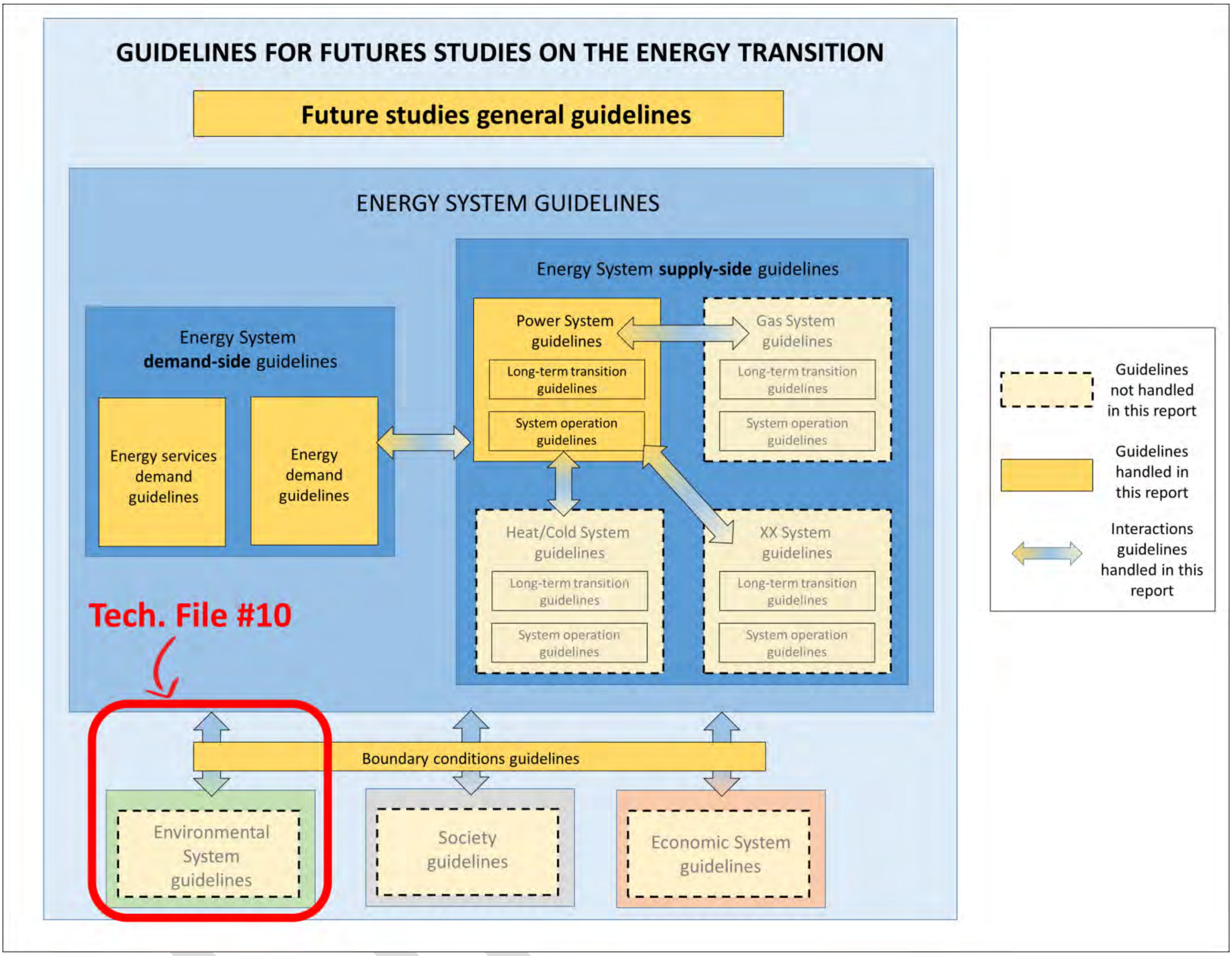
The goal of this project is to produce a set of guidelines addressed to scenario producers. These guidelines seek to foster transparency and consistency *within* future studies and to develop a common language *across* studies. By defining a number of important items which are key to deal with in future studies, we actually propose a study template which enables a better understanding of the location of each proposed scenario on the tree of possible transitions. Once again, the objective is not to *rank* studies, or scenarios, but rather to *compare* them to get a better collective overview of the different aspects of the transition (what are the differences between studies in terms of driving questions, hypotheses, models, methodology, results?).

Several aspects of the energy transition are handled in these technical files. However, on the energy supply-side only the power system has been studied. The main reason for this choice is that we had to start from somewhere with limited resources, and the power system seemed to be a key system to study in the energy transition context, towards a low-carbon economy, as shown by the growing number of future studies focusing on this system. However, the guidelines we propose could be completed by analyzes on the other energy supply-side systems (the gas system, oil system, heat system and so on).

Each technical file tackles several aspects of future studies for the power (and energy) transition. Here is the complete list of the technical files produced during the project:

#	Technical file title
1	Future studies on the energy transition
2	Energy transition models
3	Boundary conditions for energy transition scenarios
4	Long-term evolution of energy consumption in energy transition scenarios
5	Lifestyles and consumption behaviors in energy transition scenarios
6	Long-term evolution of the power system supply-side in energy transition scenarios
7	Power system operation in energy transition scenarios
8	Impact assessment in energy transition scenarios
9	Transition desirability in energy transition scenarios
10	Environmental assessment of energy transition scenarios
11	Economic evaluation of energy transition scenarios
12	Employment assessment of energy transition scenarios

Altogether, these files cover the fields described on the following map of the guidelines for future studies on the energy transition. The document you are reading covers the red-circled topics.



In addition to these technical files, three complementary notes have been produced as specific focuses on the following aspects: material criticality in energy transitions (in French, to be translated and added to technical file #10), levelized cost of electricity (LCOE) in energy transition future studies (in French) and discount rate in energy transition future studies (in French).

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Table of content

Reading keys

Explanation box, containing key information for a better overall understanding of the subjects.

Recommendations to scenario producers:

These boxes contain the recommendations for scenario producers.

The word "should" means that scenario producers, if they are to follow the guidelines, must substantiate the corresponding point. The words "may" or "might" relates to suggestions, ideas to help the scenario producer respond to the point.

Questions in italic are examples of questions scenario producers might ask to substantiate the points. They are here in an illustration purpose.

Phrases in italic relate to words which are being defined and will be subsequently used in the framework.

Phrases which are highlighted in yellow refer to other technical documents of this series.

I. Environmental assessment

A. The environment is a surrounding system for human societies

The environment is considered in this report as a *surrounding system*. In this report, the *core system* is the energy system or some of its components (such as the power system); surrounding systems are systems in which the core system operates (society, the economy, or the environment).

However, the environment has a special position among surrounding systems, as it surrounds both the core system and economic and social systems. By surrounding, we mean that the environment also contains the other systems.

Environment can be defined as follows (André, Delisle, & Revéret, 2009): environment is an organized, dynamic and evolving system composed of natural elements (physical, chemical and biological) and of human elements (economical, political, social and cultural) in which living organisms operate (including human activities) and in which they affect these living organisms (and human activities) either directly or indirectly, immediately or on the longer term.

This definition highlights the inclusiveness of the environment. It also highlights its complex and dynamic nature: organisms act within the environment, which in turn affects the environment, and these environmental changes may affect back the organisms directly or indirectly, following complex feedback loops structures with different temporalities.

Seen from human societies, the effects back on humans may be delayed (such as carcinogenic effects of air pollution, or extreme weather events due to GHG emissions), may happen remotely (such as effects of gaseous emissions in the atmosphere), they can be combined (such as climate change effects and habitat fragmentation effects on biodiversity, in turn affecting crop productivity), they can be non-linear with threshold effects (such as climate change with regards to the amount of GHG emissions).

Environment can be described along different space scales:

- Micro environment is at the level of the individual (its habitat for non-human living organisms, its dwelling or neighborhood for human beings)
- Meso environment is at the level of a group of individuals, or society (enlarged habitat, city, region or State)
- Macro environment is at the continent or world level (biosphere, human life)

Human beings have different decision processes and levers at these different scales to perform activities. These activities may interact with their micro or meso environment (local impacts, such as air pollution) or on their macro environment (global impacts, such as climate change or sea level rise, stratospheric ozone depletion, ocean acidification and so on).

In this section, we tackle the following interactions between the energy system evolution and the environment: greenhouse gases (GHG) emissions; impacts on the biosphere; land use; air pollution; water use; solid wastes; and noise. Note that questions on resource availability and criticality are dealt with in section about Boundary conditions.

Studies we reviewed generally include considerations on GHG emissions; a few consider air pollution; a few consider mineral resources use. Other impacts are rarely talked about, and never quantified.

B. Greenhouse gases (GHG) emissions

Greenhouse gases emissions have several global impacts such as climate change and sea level rise. These impacts are global because the atmosphere blends within about a year. Hence no matter where they are emitted, they quickly get blended all around the Earth.

Technically speaking, greenhouse gases are atmospheric gases which intercept infrared radiations from the Earth surface. Some of them are naturally present in the atmosphere, some others only come from human activities; some are naturally present but human activities significantly increase their amount in the atmosphere on the long-term. Increasing their amount on the long-term leads to modify (on the long-term) the radiative balance of the

Earth, storing more energy within the Earth system, in turn modifying the stable environment in which ecosystems developed.

The consequences of these processes are various: increase of the global average temperature, sea level rise (because of water dilatation due to this temperature increase and because of ice sheets melting); increase of the frequency and/or magnitude of extreme weather events (droughts, heat waves, storms…)… These consequences are usually called "physical risks"[1].

Future studies logically focus on those GHGs which are emitted by human activities and for which those emissions lead to a significant increase of their amount in the atmosphere. Several practices can be found in future studies when it comes to GHG considerations. They all depend on the driving questions and perimeter of the study.

Within our scope, one study does not consider greenhouse gases (GHG) at all. Its driving questions are about technical aspects of prototypical power systems, and costs of these different systems (ADEME, 2015). All the other studies include considerations on GHGs.

The differences between these studies pertain to the GHG emissions models (that is, their computation in a consistent way vis-à-vis the proposed core system evolution within each scenario) which are used.

Some studies model *energy-related* CO_2 emissions only (ADEME / Artelys, 2018; Agora Energiewende, IDDRI, 2018; ENTSOG/ENTSO-E, 2018). Energy-related CO_2 emissions are those emissions produced when carbon-based fuels are burnt, such as within ICE vehicles, in gas or fuel boilers, in gas or coal power plants, in gas industrial ovens and so on. Usually, the studies considering only energy-related CO_2 emissions focus on the power system only, or on the energy system only.

Some other studies model *process-related* CO_2 emissions and other GHG emissions, in addition to energy-related CO_2 emissions (ADEME, 2012; ANCRE, 2013; ECF, 2010; European Commission, 2011; Greenpeace, 2015; OECD/IEA, 2017; SFEN, 2018)[2]. Process-related CO_2 emissions are those emissions due to some transformation processes within the industry, such as cement or glass production which emit CO_2 during specific phases of their transformation. The other GHGs which are usually considered are those included in the UNFCCC framework for GHG reporting for countries (UNFCCC, 2014): carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF6) and nitrogen trifluoride (NF3). Those GHG are emitted from agriculture activities, operation of the energy system, some industrial processes and from the use of refrigerants (ANCRE, 2013). The core system of these studies usually is the whole energy system and the agriculture system together.

Some studies modeling energy-related CO_2 emissions only also roughly quantify the evolution of process-related CO_2 emissions and other GHG emissions in order to provide an all GHG reduction assessment (Association négaWatt, 2014; Fraunhofer ISE, 2015). This rough estimate is largely uncorrelated to the proposed energy system evolution, this is why these emissions cannot be said to be modeled.

Some studies also include, in addition, the CO_2 emissions or storage due to Land Use, Land Use Change and Forestry (LULUCF) (Association négaWatt, 2017; European Commission, 2016; IIASA, 2012). These emissions are those due to the fact that different types of lands contain different amounts of stored carbon, so changes in land use and forestry practices may release CO_2, or store carbon. The core system of these studies includes the energy system, the agriculture system as well as the different land uses.

The larger the core system of the study, the more comprehensive the GHG assessment can be.

One study we reviewed models energy-related CO_2 emissions only for the power system supply-side, but with a footprint approach (Hammond, Howard, & Jones, 2013). This approach further questions the choice of technologies used for the transition to produce, store, transport and distribute electricity.

[1] Another type of risk is often talked about: transition risks. These risks are actor specific and are linked to the fact of performing an energy transition. They are talked about in terms of inertia of the socio-technical systems which evolve during the transition (in the Future studies section), in terms of stranded assets and sunk costs (in the Economic evaluation section) as well as in terms of desirability (in the Desirability section and employment section).

[2] (Greenpeace, 2005; Greenpeace, 2012; Greenpeace, 2015; Greenpeace EREC, 2008) are not transparent enough to be sure about their approach.

Recommendations to scenario producers

A strategy about GHGs emissions assessment should be defined and substantiated with regards to the driving questions. The following aspects should be considered:

- Impact definition: GHGs which are included in the assessment
- Type of assessment approach which is used (territory, or footprint)
- Inventory: Activities and processes which are considered as sources of these GHGs emissions
- Modeling methodology

C. Impacts on biosphere

The biosphere is the set of all living organisms and their habitats, that is, the set of all ecosystems surrounding us. The biosphere is usually considered as important for human beings for the "ecosystem services" it brings to us.

These services are only the visible part of all the interactions within the biosphere. Within an ecosystem, species interact with each other, and within species individuals interact with each other. Ecosystem services are some of the emergent patterns of all those complex interactions. More specifically, they are the ones which are important to us as human beings. Focusing only on the last links providing the service (for example, focusing on bees for pollination instead of understanding the whole net of ecosystem interactions between bees and their environment, would it be physical, chemical or trophic environment) is a narrow view. It fails to see that the service is actually sustained by a whole set of processes and interactions with other elements of the biosphere. As such, the ecosystem services approach does not enable to uncover all the risks leading to the decline and extinction of the services it aims to study.

A classical measure of biosphere integrity is that of biodiversity, a concept which includes the genetic diversity within each species, the diversity of species, and the diversity of ecosystems.

The greatest causes of biodiversity losses are the following (IPBES, 2019):

- Habitat transformation through land use / sea use change. "Agricultural expansion is the most widespread form of land-use change, with over one third of the terrestrial land surface being used for cropping or animal husbandry. This expansion, alongside a doubling of urban area since 1992 and an unprecedented expansion of infrastructure linked to growing population and consumption, has come mostly at the expense of forests (largely old-growth tropical forests), wetlands and grasslands" (IPBES, 2019). Habitat transformation can also happen through habitat fragmentation (e.g. due to the road, or electricity networks), habitat space reduction (due to the proximity of human activities, noises).
- Overexploitation of animals, plants and other organisms mainly via harvesting, logging, hunting and fishing.
- Climate change. "The frequency and intensity of extreme weather events, and the fires, floods and droughts that they can bring, have increased in the past 50 years, while the global average sea level has risen by 16 to 21 cm since 1900, and at a rate of more than 3 mm per year over the past two decades. These changes have contributed to widespread impacts in many aspects of biodiversity, including species distributions, phenology, population dynamics, community structure and ecosystem function" (IPBES, 2019).
- Many types of pollution, as well as invasive alien species, are increasing, with negative impacts for nature. "Marine plastic pollution, untreated urban and rural waste, pollutants from industrial, mining and agricultural activities, oil spills and toxic dumping have had strong negative effects on soil, freshwater and marine water quality and the global atmosphere" (IPBES, 2019).

In freshwater ecosystems, a series of combined threats that include land-use change, water extraction, exploitation, pollution, climate change and invasive species, are prevalent.

No energy transition future study to our knowledge quantitatively assesses the evolution of the biosphere for its different scenarios. However, (Association négaWatt, 2017) provides information about the variation direction of the overall impact on biosphere of its "négaWatt" scenario compared to its Reference scenario. (European

Commission, 2011) provides information about the impacts of the energy system on biosphere without explicitly linking those considerations to its different scenarios.

Most likely, computationally modelling biosphere and its integrity is not realistic. However, a qualitative assessment based on demographic evolution, on energy and material extraction, on water use, on land use, on built infrastructure (would it be demand side infrastructure such as roads, or supply-side infrastructure such as hydropower dams) and on the specific environmental practices of the different economic agents may be useful to inform the energy transition debate.

Recommendations to scenario producers

A strategy about biosphere integrity assessment should be defined and substantiated with regards to the driving questions. The following aspects may be considered:

- Impact(s) definition: Drivers of biosphere evolution which are considered in the assessment (habitat transformation, exploitation of living organisms, climate change, pollution, invasive alien species)
- Type of assessment approach which is used (territory, or footprint)
- Inventory: Activities and processes which are considered as sources of the biosphere evolution.
- Modeling methodology. The methodology can be qualitative in order to trigger discussion with stakeholders and to inform the debate about the interactions between the energy transition and biosphere. *For example, for each considered activity in the scenario, does it improve/degrade habitat, does it increase/decrease the exploitation of living organisms and so on.*

D. Land use change

Land use and land use change impacts are by essence local (they happen where the land is used). However, these impacts may be indirect, such as when agricultural production switches from food use to biofuel production use (no direct land use change), triggering in turn deforestation to farm in order to produce the missing food (indirect impact).

As previously mentioned, land use changes have significant impacts on carbon emissions or storage, as different types of soil and vegetation store more or less carbon. They also have impacts on the biosphere. Furthermore, those changes may be more or less desirable by local populations (see section on desirability).

As previously described, the drivers of land use change at the world level is agriculture. However, energy system evolution may also greatly affect land use both through supply-side installations[3] and through demand-side evolutions.

Concerning the former aspect (supply-side), land may be differently occupied by supply-side installations: either land is entirely dedicated to the installation, or it can be used for other purposes (Criqui, 2013). For example, ground PV installations may cover other activities from the Sun, hydropower dams may be used for irrigation and leisure activities (or even for installing floating PV panels), and so on. Some installations may also reduce the number of activities which can be performed on their land, causing land use conflicts (and desirability issues). For example, off-shore installations may cause conflicts with fishery activities. Supply-side evolution may also lead to evolutions in biofuel production, or energy wood production. These productions are actually photosynthesis exploitation through agriculture and forestry. As such, their evolutions may lead to direct or indirect land use changes.

Concerning the latter aspect (demand-side), as explained in the lifestyles and consumption section, urban planning and transportation networks are two key technical and organizational systems which influence energy demand.

A few studies assess the evolution of land uses per say (that is, not only for computing LULUCF GHG emissions) either qualitatively or quantitatively through the area of land used by the energy, or power, system supply-side (ADEME, 2015; ANCRE, 2013; Association négaWatt, 2017).

[3] For a comprehensive assessment of the space required to extract and refine primary energy, see (Smil, 2015).

Recommendations to scenario producers

A strategy about land use change assessment should be defined and substantiated with regards to the driving questions. The following aspects may be considered:

- Impact(s) definition: specificities of lands (area, current land use(s), types of land…). *For example, does the study only assess total surface of land use change, or does it assess land use change along different types of lands (forests, marshlands, croplands…), or does it assess the nature of the changes (e.g. from fishery to electricity production)?*
- Type of assessment approach which is used (territory, or footprint)
- Inventory: Activities and processes which are considered as sources of land use changes.
- Modeling methodology. The methodology can be qualitative in order to trigger discussion with stakeholders and to inform the debate about the land use changes involved by the proposed energy transitions. Desirability aspects such as impacts on human ecology or on employment may be discussed. Such discussions are much more concrete than the sole indication of the total surface of land which changed during the transition.

E. Air pollution

Air pollution may be defined as any atmospheric constituent present as a result of anthropogenic activity or natural processes that causes adverse effects to humans, animals, vegetation, or materials. Air pollution is an impact on the meso-environment (typically, city scale).

The main adverse effects usually considered in the public debate are effects on human health (respiratory and cardio-vascular diseases, cancers) and acid rains. According to the World Health Organization, 1.3 million people die each year for air pollution reasons in the world (« OMS | Effets sur la santé de la pollution de l'air en milieu urbain », 2019).

The main air pollutants which are considered in national legislations and in future studies are the following (IIASA, 2012; Liu, 2015):

- Sulfur dioxide (SO_2). It affects human health and it is a precursor to acid rains and particulate matter. It is produced by the burning of fossil fuels contaminated with sulfur compounds (such as coal or heavy oil) and copper extraction.
- Nitrogen oxides (NOx). It affects human health and it is a precursor to acid rains. It is produced through the combustion of fuels at high temperature such as in ICE vehicles or power plants, and through agricultural fertilization.
- Carbon monoxide. It is a highly toxic gas, inhibiting respiratory functions. Carbon monoxide poisoning is the most common type of fatal air poisoning in many countries (Omaye, 2002). It is mainly produced by ICE vehicles.
- Volatile organic compounds (VOC). They have effects on human health. They can have anthropic sources such as the use of various chemicals such as paints and coatings, ICE vehicles and other sources.
- Particulate matter PM2.5 and PM10. They are particles which can be inhaled and are classified by size. The smaller the particle, the deeper in the lungs it can get. They affect human health. They are produced by industrial combustion, agriculture, ICE vehicles, and construction industry, under the form of dust, soil, soot or smoke.

Some of these pollutants interact with each other and with other atmospheric components (called precursors) to produce secondary air pollutants following complex interactions.

A few studies model air pollution: (IIASA, 2012; OECD/IEA, 2017) use the GAINS model to do so. (ADEME, 2012) uses another model first computing the emissions of primary pollutants and precursors of secondary pollutants, and then assessing air quality in urban areas through a second module.

Recommendations to scenario producers

A strategy about air pollution assessment should be defined and substantiated with regards to the driving questions. The following aspects may be considered:

- Impact(s) definition: air pollutants which are considered in the study
- Type of assessment approach which is used (territory, or footprint)
- Inventory: Activities and processes which are considered as sources, or precursors of the pollutants (both primary and secondary)
- Modeling methodology

F. Water use

Water use may affect sea water and/or freshwater; freshwater can be running water or fossil water (non renewable water, typically groundwater in an aquifer). It may affect water quality and/or water flow. Water quality can be measured along several dimensions (temperature, pH, amount of dissolved oxygen, amount of toxic substances…). Water use has local impacts.

Water use affects the biosphere. For example, thermal power plants (nuclear or fossil fuel power plants) need a cooling source to properly operate. Some of them use water as a cooling source, in turn releasing water that is warmer than the ambient water. Local ecosystems may be sensitive to these releases. Legislations control local water temperatures, sometimes leading to power plants' temporary shutdown in case of heat waves. Hydropower dams also have impacts on the biosphere (other than the direct submersion of the local ecosystems), preventing sediments and species to move freely.

Water use can also directly affect human activities (fishery, irrigation, industrial cooling, leisure activities…), or human direct water consumption, hence rising water use conflicts and desirability questions.

Water is used in nearly all industrial processes within the energy sector (extraction, processing of fossil fuels and uranium, biomass production and conversion, thermal, nuclear, geothermal, hydro- electricity production). As a result, the energy sector represents nearly 50 % of water withdrawal in developed countries[4] (Lemoine, 2016).

No future study about energy transition quantitatively tackles the question of water use to our knowledge. Some studies provide qualitative considerations about this aspect: (Association négaWatt, 2017) qualitatively considers the variation direction of water consumption in its "négaWatt" scenario compared to the Reference scenario. (European Commission, 2011) provides qualitative considerations on this aspect without linking them explicitly to its different scenarios.

Recommendations to scenario producers

A strategy about water use assessment should be defined and substantiated with regards to the driving questions. The following aspects may be considered:

- Impact(s) definition: specificities of the water which is used (sea water, freshwater); specific indicators which are used (volume of consumed water, water temperature…)
- Type of assessment approach which is used (territory, or footprint)
- Inventory: Activities and processes which are considered as sources of water use
- Modeling methodology. As the considered impacts are local, local conditions would have to be known in order to precisely assess and discuss the impacts of water use evolution. As a result, qualitative general considerations can be provided and some case studies could be examined to illustrate specific effects of the proposed energy transition. Important aspects to discuss are impacts on biosphere and desirability aspects (for individuals and businesses).

[4] Water withdrawal is the amount of water withdrawn from a source whereas water consumption is the amount of water which is not released back in the source.

G. Hazardous and nuclear solid wastes

Solid wastes are of various natures. However some of them can be reused, or recycled, or incinerated, biologically or chemically treated. After these options, some wastes remain and are landfilled. Part of these wastes are categorized as "hazardous", other as non-hazardous, with regards to the landfilling practices (Méhu, 2016). Ultimate nuclear wastes[5] are treated, stored and landfilled in separate processes.

These solid wastes have local impacts if properly stored. They may have impacts on the meso-environment in case leachate risks[6] are not properly managed, polluted water then circulating in the environment. However, several practices are applied to avoid leachate being formed and being released in the environment: waste can be vitrified, as is performed for nuclear waste, preventing any contact with water, or landfills can be equipped with leachate collection and treatment systems.

Numerous activities linked with the energy system generate hazardous wastes (SEPA/Environment and heritage service/Environment Agency, 2003): different activities in fossil fuels extraction and transformation/refining; combustion of fossil fuels in power plants and in industrial processes generate ashes and residues which ultimately have to be landfilled; end-of-life vehicles contain different substances considered as hazardous; some end-of-life batteries are hazardous waste… These wastes have various effects on, or pose various risks for, human health and the environment in case of direct exposure (Directive 2008/98/EC on waste, 2008): they can be explosive, highly flammable, irritant, harmful, toxic, carcinogenic, corrosive, infectious, mutagenic, ecotoxic…

Nuclear industry generate nuclear wastes, during and after uranium extraction, uranium treatment and enrichment, residues from nuclear power production, radioactive waste from power plant dismantling. These wastes are categorized according to two criteria: radioactivity level and radioactivity duration. These wastes mainly have long-term carcinogenic effects on humans, and living organisms, in case of direct exposure (« Answers to Frequently Asked Questions (FAQs) by UNSCEAR », 2019).

A few future studies on the energy transition consider solid waste. (Association négaWatt, 2017) estimates the variation direction of the amount of waste (without waste distinction) produced from its Reference scenario to its négaWatt scenario. (European Commission, 2011) assesses the variation direction of the amount of nuclear waste which will have to be managed in its different scenarios, compared to its Reference scenario.

Recommendations to scenario producers

A strategy about hazardous and nuclear waste assessment should be defined and substantiated with regards to the driving questions. The following aspects may be considered:

- Impact(s) definition: specificities of wastes which are considered (hazardous or not, nuclear, type of effect on human health or the environment, radioactivity level, radioactivity duration…). *For example, does the study only assess the total amount of solid waste from the energy sector, or does it assess the amount of nuclear, and hazardous waste?*
- Type of assessment approach which is used (territory, or footprint)
- Inventory: Activities and processes which are considered as sources of the considered wastes.
- Modeling methodology. The methodology can be qualitative in order to trigger discussion with stakeholders and to inform the debate about waste generation and management involved by the proposed energy transitions. Desirability aspects may be discussed. Such discussions are much more concrete than the sole indications of the total amount of generated waste during the studied transitions.

[5] That is, those which are considered as not usable in future industrial processes.
[6] Leachate is water which passed through the waste and extracted soluble or suspended solids within the waste.

H. Noise

Noise can be defined as annoying sound, which is a partly subjective definition. However, above a certain volume level, any sound is annoying for human beings (« Bruit. Définitions - Risques - INRS », 2019). Noise is a local impact, as sound level rapidly decreases with distance to the sound source.

Noise has effects on health, mainly on auditory capacities, and generates stress and sleep problems.

Noise is generated by air movement, hence technically any process involving movement can be a source of noise. However, as noise has a subjective definition, it has to be linked with desirability questions. Most commonly considered sources of noise within the energy system is noise from passenger or freight transportation (ground or air transportation), and from the operation of some power plants (such as wind turbines).

Noise is not considered in the future studies we reviewed.

Recommendations to scenario producers

A strategy about noise assessment should be defined and substantiated with regards to the driving questions. The following aspects may be considered:

- Impact(s) definition: what specific aspects of noise are considered
- Type of assessment approach which is used (territory, or footprint)
- Inventory: Activities and processes which are considered as noise sources
- Modeling methodology. As the considered impacts are local, local conditions would have to be known in order to precisely assess and discuss the impacts of noise. As a result, qualitative general considerations can be provided and some case studies could be examined to illustrate specific effects of the proposed energy transition. An important aspect of noise impact is the desirability for individuals.

Bibliography

ADEME. (2012). *L'exercice de prospective de l'ADEME - « Vision 2030-2050 »*.

ADEME. (2015). *Un mix électrique 100% renouvelable ? Analyses et optimisations*.

ADEME / Artelys. (2018). *Trajectoires d'évolution du mix électrique 2020-2060 - Synthèse*.

Agora Energiewende, IDDRI. (2018). *L'Energiewende et la transition énergétique à l'horizon 2030*.

ANCRE. (2013). *Scénarios de l'ANCRE pour la transition énergétique*.

André, P., Delisle, C., & Revéret, J.-P. (2009). *Évaluation des impacts sur l'environnement* (3e édition). Consulté à l'adresse http://www.presses-polytechnique.ca/fr/evaluation-des-impacts-sur-l-environnement-l-3e-edition

Answers to Frequently Asked Questions (FAQs) by UNSCEAR. (2019). Consulté 29 mai 2019, à l'adresse United Nations Scientific Committee on the Effects of Atomic Radiation website: https://www.unscear.org/unscear/en/faq.html

Association négaWatt. (2014). *Scénario négaWatt 2011-2050 - Hypothèses et méthode*.

Association négaWatt. (2017). *Scénario négaWatt 2017-2050 | Dossier de synthèse* (p. 48).

Bruit. Définitions - Risques - INRS. (2019). Consulté 29 mai 2019, à l'adresse INRS website: http://www.inrs.fr/risques/bruit/definitions.html

Criqui, P. (2013). *Quatre trajectoires pour la transition énergétique* (p. 15).

Directive 2008/98/EC on waste. , Pub. L. No. 32008L0098, OJ L 312 (2008).

ECF. (2010). *Roadmap 2050 - A Practical Guide to a Posperous, Low-Carbon Europe*.

ENTSOG/ENTSO-E. (2018). *TYNDP 2018 - Scenario Report* (p. 56).

European Commission. (2011). *Energy Roadmap 2050 - Impact assessment and scenario analysis*.

European Commission. (2016). *EU reference scenario 2016: energy, transport and GHG emissions : trends to 2050.* Luxembourg.

Fraunhofer ISE. (2015). *What will the energy transformation cost? - Pathways for transforming the German energy system by 2050*.

Greenpeace. (2005). *Energy revolution: a sustainable pathway to a clean energy future for Europe* (p. 32).

Greenpeace. (2012). *Energy [R]evolution - A sustainable world energy outlook 2012* (p. 340).

Greenpeace. (2015). *Energy [R]evolution - A sustainable world energy outlook 2015* (p. 364).

Greenpeace EREC. (2008). *energy [r]evolution - A sustainable global energy outlook* (p. 212).

Hammond, G. P., Howard, H. R., & Jones, C. I. (2013). The energy and environmental implications of UK more electric transition pathways: A whole systems perspective. *Energy Policy*, *52*, 103-116. https://doi.org/10.1016/j.enpol.2012.08.071

IIASA. (2012). Energy Pathways for Sustainable Development. In *Global Energy Assessment Towards a Sustainable Future*.

IPBES. (2019). *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (p. 39).

Lemoine, Y. (2016). *Water for Energy - Issues at stake and interests of water assessment tools*. Présenté à ISIGE Mines ParisTech. ISIGE Mines ParisTech.

Liu, H. (2015). *Atmospheric Environment*. Présenté à School of Environment, Tsinghua University. School of Environment, Tsinghua University.

Méhu, J. (2016). *Waste treatment strategies*. Présenté à INSA Lyon. INSA Lyon.

OECD/IEA. (2017). *World Energy Outlook 2017* (p. 782).

Omaye, S. T. (2002). Metabolic modulation of carbon monoxide toxicity. *Toxicology*, *180*(2), 139-150. https://doi.org/10.1016/S0300-483X(02)00387-6

OMS | Effets sur la santé de la pollution de l'air en milieu urbain. (2019). Consulté 28 mai 2019, à l'adresse WHO website: https://www.who.int/phe/health_topics/outdoorair/databases/health_impacts/fr/index1.html

SEPA/Environment and heritage service/Environment Agency. (2003). *Hazardous waste - Interpretation of the definition and classification of hazardous waste* (p. 236).

SFEN. (2018). *Le nucléaire français dans le système énergétique européen*.

Smil, V. (2015). *Power Density - A Key to Understanding Energy Sources and Uses*. MIT Press.

UNFCCC. (2014). *Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013 Addendum Part two: Action taken by the Conference of the Parties at its nineteenth session* (p. 54).

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Criticité des métaux et autres matériaux dans les scénarios de transition

Fiche technique – Pour discussion. Version française.

Table des matières

Clés de lecture

Encart explicatif, contenant des informations clés permettant une meilleure compréhension globale du sujet.

Recommandations pour les producteurs de scénarios :

Ces cadres contiennent des recommandations pour les producteurs de scénarios.

Le terme "devrait" (ou "devraient") signifie que les producteurs de scénarios, s'ils veulent suivre les lignes directrices, doivent justifier le point correspondant. Les termes "peut" ou "pourrait" indiquent des suggestions, des idées pour aider le producteur du scénario à répondre à ce point.

Les questions en italique sont des exemples de questions que les producteurs pourraient se poser pour étayer leurs arguments. Elles sont ici dans un but d'illustration.

Les phrases surlignées en jaune font référence à d'autres documents techniques de cette série.

I. La criticité des métaux : un enjeu complexe, potentiellement dimensionnant, et peu traité dans les études prospectives sur la transition énergétique

A. Un enjeu clé sous-estimé malgré un intérêt croissant

Les métaux et matériaux sont, avec les énergies fossiles, une des principales **ressources de stock** que nous utilisons à grande échelle sur la planète. Leur exploitation à l'échelle mondiale a fortement augmenté dans les années 2009-2010. Ainsi, leur possible épuisement pose question, comme cela est résumé dans l'étude (ADEME, 2017) :

« La croissance exponentielle de la demande risque d'être supérieure au rythme de la croissance des capacités d'exploitation. En conséquence des pénuries sur certaines matières minérales pourraient survenir dans un avenir proche (10 ans). Dans une croissance continue de la demande à 2 ou 3% le recyclage ne pourra pas répondre à cet accroissement et restera à moins de 20% des approvisionnements nécessaires.

Par ailleurs les conséquences environnementales locales de l'exploitation de ces gisements en limiteront l'acceptabilité sociale si elles ne sont pas totalement maîtrisées. En outre l'augmentation des consommations énergétiques de ce secteur risque de rentrer en confrontation avec la lutte contre le changement climatique. Ce n'est probablement pas l'épuisement des métaux et minéraux qui est à craindre mais très certainement la fin de l'extraction et de la disponibilité faciles. »

Or, nombreuses sont les études prospectives proposant des scénarios de transition et qui n'étudient pas ces questions de criticité des métaux et matériaux. Certaines proposent parfois des transitions au niveau mondial, en faisant appel souvent à des changements importants incluant une large part d'énergies renouvelables, de grandes capacité de stockage, un fort développement du véhicule électrique et/ou un renforcement du réseau. Comme nous allons le voir, l'analyse de la faisabilité technique de ces scénarios comporte un réel **angle mort** si la question des matériaux n'est pas abordée. Parmi les rares études qui prennent en compte quantitativement ces questions, on peut citer (Association négaWatt, 2018), qui présente un bilan de besoin de certains matériaux de son principal scénario.

Plus généralement, la recherche sur ces contraintes est assez restreinte en comparaison à l'importance manifeste du sujet, mais se développe tout de même : (Bonnet, Carcanague, Hache, Seck, & Simoën, 2019) montre à travers un graphique du nombre annuel de publications l'intérêt croissant de la littérature sur ces questions, mais l'étude conclut par ailleurs qu'il est difficile de faire émerger un consensus sur le risque d'approvisionnement lié à une matière première car il existe une grande sensibilité dans les résultats selon les méthodes et les données.

B. Criticité : une analyse multidimensionnelle de la dépendance aux ressources minérales

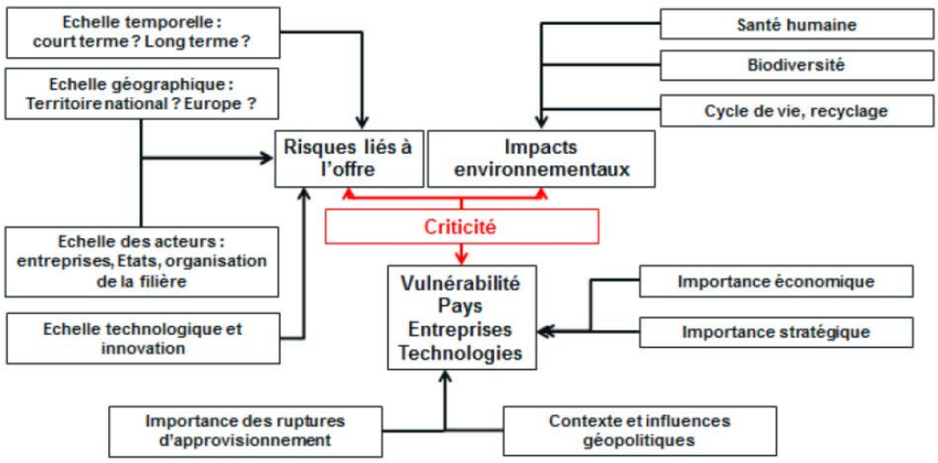
La dépendance aux ressources minérales est communément appelée « criticité ». Le principal élément de complexité dans l'étude des contraintes sur l'approvisionnement en métaux vient de son **caractère multidimensionnel**. En effet, prendre en compte l'aspect technique uniquement ne permet pas d'évaluer correctement le niveau de criticité : il existe des métaux critiques et non rares, tout comme des métaux critiques et recyclables.

Ainsi, comme cela est résumé dans l'étude (Bonnet, Carcanague, Hache, Seck, et al., 2019) :

« La criticité n'est ni universelle, ni intemporelle, ni binaire (Graedel and Reck, 2016). Elle varie en réalité en fonction des intérêts économiques (commerciaux, technologiques, financiers) et politiques (sécurité, défense, politique étrangère) d'un État, dont elle est nécessairement le reflet. Elle constitue également une clé de lecture pour les relations de cet État avec ses partenaires sur la scène internationale. La nécessité de prendre en compte la dimension géopolitique et d'en affiner la mesure quantitative et qualitative, dans les études sur la criticité apparaît ainsi comme un défi essentiel, à la fois pour le chercheur et le décideur. »

La criticité peut être vue comme **un ensemble de risques**, de nature géopolitique, économique, lié à la production, environnemental ou social :

Figure 11: Évaluer la criticité des matières premières



Source : auteurs, tiré de Helbig et al., 2016.

Source : (Bonnet, Carcanague, Hache, Seck, et al., 2019)

C. Les grandes familles de métaux et les incontournables de la transition énergétique

(ADEME, 2017) propose dans ses annexes une taxonomie claire pour catégoriser les métaux (voir la source pour une taxonomie plus complète). Une première distinction importante est relative à leur concentration dans la croûte terrestre :

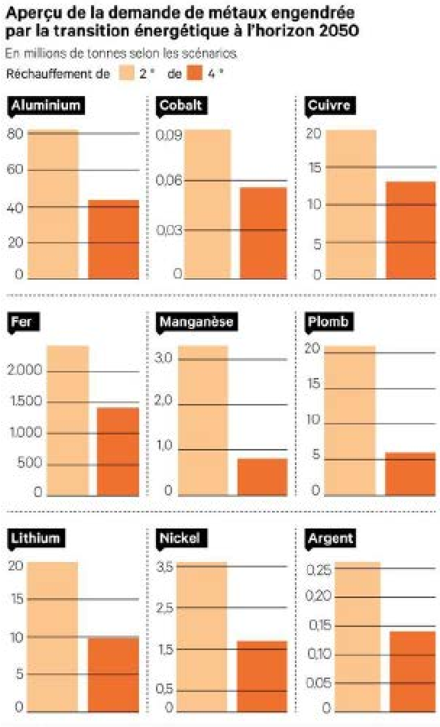
- au-dessus de 1000 ppm, on trouve les **métaux dits « abondants »**, comme le silicium ou l'aluminium.
- entre 1 et 1000 ppm, ce sont les **métaux rares** (ou « peu abondants »). Il en existe de nombreux, dont le plomb, le cuivre, le zinc, le nickel, le cobalt, le molybdène et le tungstène.
- en-dessous de 1 ppm, on trouve les **métaux « très rares »**. Parmi ceux-ci, on compte les métaux « précieux » (or, argent, et les 6 platinoïdes) et 3 autres métaux : l'antimoine, le sélénium et l'indium.

Un second point important est l'appellation **« terres rares »**. Celle-ci désigne un groupe précis de 16 ou 17 éléments qui ne sont en fait pas si rares. Ce groupe comprend les 15 éléments de la famille des Lanthanides (57 à 71) et l'yttrium. Tous ont des propriétés proches et sont pratiquement toujours associés dans leurs gisements. Le scandium est parfois ajouté à la liste. Leur appellation date d'une période où on les pensait vraiment rares, mais ils ont en réalité un niveau de rareté de l'ordre de celle des « métaux rares ». En revanche, leurs gisements ont la particularité d'être très localisés.

Parmi l'ensemble des métaux, certains sont **sollicités plus ou moins fortement** par les nombreuses technologies habituellement mobilisées dans les **scénarios de transition** : les différentes filières de solaire photovoltaïque nécessitent silicium, argent, tellure, galium et indium, les batteries font appel entre autres au lithium, nickel, cobalt, les besoins de renforcement réseau nécessitent du cuivre, certains types d'éoliennes ainsi que les voitures électriques nécessitent des terres rares (néodyme, praséodyme et dysprosium notamment) pour leurs aimants permanents, les véhicules hydrogène nécessitent des platinoïdes, etc.

Voici à titre d'illustration un aperçu de l'augmentation de la demande pour certains métaux dans un contexte de scénarios dits « deux degrés » :

Graphique 1 – Demande médiane en métaux pour les technologies éoliennes à l'horizon 2050



Évolution de la demande en métaux dans l'hypothèse d'un réchauffement de 2° C et de 4° C, en comparaison avec un scénario 6° C.

Source : Les Échos ; *la Banque mondiale.*

Source : (IFRI, 2018)

Egalement, voici quelques éléments clés concernant la criticité de certains métaux en particulier :

- Pour ce qui est de la situation des **terres rares**, deux chiffres clés sont à retenir. D'une part, environ 90% de la production actuelle se trouve en Chine, et d'autre part environ 80% de la demande vient des besoins en aimants permanents. Ainsi, l'analyse de la criticité passe nécessairement par un volet géopolitique. A ce titre, voir l'étude "Rare Earths and China: A Review of Changing Criticality in the New Economy" (Seaman, 2019).
- Pour le **lithium,** la criticité géologique ne semble pas être trop importante. En revanche, comme pour les terres rares, la criticité géopolitique est bien réelle. En effet, le lithium est produit de façon très concentrée, en grande majorité dans le « triangle du lithium », c'est-à-dire en Bolivie, au Chili et en Argentine par une poignée d'entreprise. De plus, la part de la demande en lithium venant des batteries est importante et devrait augmenter. Sur ce métal, voir, par exemple, l'étude "Critical raw materials and transportation sector electrification: A detailed bottom-up analysis in world transport" (Hache, Seck, Simoen, Bonnet, & Carcanague, 2019).
- Pour le **cuivre** en revanche, une criticité géologique est à prévoir. Comme présenté dans l'étude (Bonnet, Carcanague, Hache, Seck, et al., 2019), une partie importante de la demande de cuivre vient du secteur électrique. Pour une modélisation de la criticité géologique sur le cuivre, entre augmentation de la demande et développement de filières de recyclage, voir le projet SURFER porté par le CNRS, le BRGM et l'ADEME.
- Enfin, au sujet d'**autres matériaux** comme le ciment, voir l'étude "The impact of Future Generation on Cement Demand: An Assessment based on Climate Scenarios" (Bonnet, Carcanague, Hache, Simoen, & Seck, 2019), ou l'étude (United States Department of Energy, 2015) qui fournit des tableaux concernant la

consommation en matériaux de différentes technologies de production d'énergie et différents types de véhicules.

D. Quelques points de départ pour mener une analyse sur la criticité dans les scénarios

Comme on l'a vu, la criticité est un paramètre aux multiples facettes. Voici un ensemble de critères et de questions qui peuvent se poser dans l'analyse de la criticité d'un métal dans un scénario (fonctionne aussi avec d'autres matériaux) :

- **Disponibilité géologique**. *Le métal est-il rare ?*
- **Dépendance entre matériaux au niveau du minerai**. *Le métal est-il le sous-produit d'un autre ?*
- **Temps de développement de la production**. *Combien de temps se passe-t-il entre les premières études sur une exploitation et son plein fonctionnement ?*
- **Filière de recyclage**. *Sait-on recycler ce métal ? A quel taux ? Quelles sont les capacités effectives ?*
- **Possibilités de substitution**. *Peut-on facilement changer de métal pour une même utilisation ? Ou bien changer de technologie pour se passer de ce métal ?*
- **Croissance de la demande**.
- **Concentration de la production**. *Combien de producteurs de ce métal ?*
- **Risque politique**
- **Contraintes environnementales et sociales**, avec notamment la disponibilité en eau pour la production du minerai et la possibilité de refus par la communauté des répercussions de son exploitation (Donella H. Meadows, Randers, & Meadows, 2004). Sur ce dernier point, il peut être important de rappeler que certaines exploitations actuelles de minerai se font dans des conditions environnementales et sociales pour le moins discutables. De plus, la notion de contraintes environnementales permet d'introduire l'**impact du changement climatique** sur ces enjeux. En effet, comme cela est développé dans l'étude (Carbone 4, 2019) : « l'activité minière est par essence particulièrement exposée aux aléas climatiques et notamment aux problématiques de gestion de la ressource en eau. » Cela illustre comment différents problèmes environnementaux peuvent être liés.

Ainsi, pour mener des analyses sur la notion de criticité dans les scénarios, on voit bien qu'une partie importante des risques dépend surtout du **narratif**, c'est-à-dire de choix faits dans la **storyline** de l'étude (voir le dossier Future studies). Ceux-ci peuvent être traités de façon qualitative. D'autres éléments peuvent être modélisés de façon quantitative, comme le développement de filières de recyclage par exemple.

Le tableau des métaux jugés critiques pour l'Union Européenne (Commission européenne, 2017) peut constituer un point de départ pour une analyse qualitative. On y retrouve 27 métaux, avec notamment leurs principaux pays producteurs, leur indice de substitution et leur taux de recyclage.

NB : Une difficulté dans l'étude de ces enjeux vient du fait que ces métaux ne sont pas seulement utilisés dans le cadre de la transition énergétique. Le secteur de la Défense, par exemple, nécessite des terres rares.

Voici un tableau d'indicateurs communément utilisés dans la littérature, parmi lesquels il peut être intéressant de s'inspirer :

Tableau 3 : Indicateurs de mesure de la vulnérabilité ou de risque sur l'offre identifiés dans la littérature selon leur fréquence d'apparition

Indicateurs de vulnérabilité économique	Indicateur de risque sur l'offre
Existence d'un substitut (Qualitatif)	Concentration de la production par pays (HHI)
Valeur des produits affectés (en % du PIB)	Gouvernance (Qualitatif ou Index de gouvernance)
Ratio de demande future sur l'offre (Qualitatif)	Temps de déplétion des ressources (années)
Valeur des matériaux utilisés (en % du PIB)	Dépendance aux coproduits (en %)
Importance de l'utilisation (en % de la population, en % du PIB)	Concentration d'entreprises minières (HHI)
Dépendance aux importations (en %)	Croissance de la demande (Qualitatif ou ratio)
Importance stratégique (Qualitatif)	Dépendance aux importations (en %, en valeur)
Capacité à innover (Qualitatif)	Potentiel de recyclage (en volume)
Variation des importations (en %)	Existence d'un substitut (Qualitatif)
Concentration des entreprises productrices (HHI)	Volatilité des prix des matières premières (en $)
Volume de consommation (en volume)	Dépenses d'exploration (en $)
Variation de la production minière (en %)	Coûts d'extraction (en $)
Recyclabilité du produit (Qualitatif)	Équilibre du marché (en volume)
	Taux d'utilisation de la capacité minière, capacité de raffinage (en %)
	Existence d'un marché financier
	Investissement dans le secteur minier (en $)
	Vulnérabilité au changement climatique (Qualitatif)
	Existence de pénurie temporaire (Qualitatif)
	Risque stratégique (embargo) (Qualitatif)
	Présence dans la croute terrestre

Sources : Tiré de Helbig et al. (2016) et de Frenzel et al. (2017)

Source : (Bonnet, Carcanague, Hache, Seck, et al., 2019)

Pour aller plus loin dans ces analyses, voir les liens vers des études citées précédemment comme le projet SURFER, ou l'étude (Bonnet, Carcanague, Hache, Seck, et al., 2019) qui présente une analyse de la criticité des matériaux de la transition énergétique en général à partir de modèles de l'AIE, puis une analyse sur la criticité du lithium du cuivre à l'aide du modèle TIAM.

NB : Les enjeux d'approvisionnement en métaux sont des sujets qui évoluent rapidement, notamment ces dernières années, et la littérature sur ces questions n'est pas encore fortement développée. Ainsi, il peut arriver que certaines données utilisées soient **obsolètes**. En effet, certaines publications s'appuient sur les données d'autres publications, etc. avec comme source initiale des bases de données trop anciennes pour être à jour.

E. Le recyclage est un levier clé mais ne peut pas tout

Le recyclage est un levier important pour réduire la criticité des métaux et matériaux, une des principales questions étant de savoir jusqu'où il est possible d'utiliser ce levier. Si le recyclage est utilisé dans le scénario, un **narratif** sur la mise en place de filières de recyclage peut être utile :

- Est-ce l'**incitation économique** qui permet le développement des filières, ce qui signifie qu'un métal est recyclé sous condition d'un débouché rentable ? (c'est majoritairement le cas aujourd'hui) Dans ce cas, le prix du métal sur les marchés est un élément important : s'il celui-ci est bas, alors l'incitation à recycler est faible.
- Est-ce qu'**une planification** par l'Etat ou un autre acteur est mise en place ? A ce titre, le marché du recyclage a pour avantage d'être connu à l'avance : le besoin en recyclage de panneaux photovoltaïques par exemple suit le rythme de la production de panneaux avec un décalage qui correspond à la durée de vie moyenne d'un panneau.
- Est-ce que l'incitation est liée à des **contraintes d'acceptabilité** liées au pays ou à la région, qui exercent ainsi une pression sur l'image du constructeur ou de l'exploitant de la technologie à recycler ?

Parmi les outils permettant d'inciter au développement des filières de recyclage on trouve : les garanties financières pour chaque installation permettant de couvrir les coûts de démantèlement en cas de faillite de l'exploitant ; le principe de Responsabilité élargie du producteur (REP) qui oblige l'entreprise qui met la technologie en question sur le marché à payer une participation au moment de cette mise sur le marché pour financer son recyclage par les filières adéquates une fois le produit arrivé en fin de vie ; des réglementations sur le taux de recyclage, etc.

Pour mener à bien une analyse quantitative sur le recyclage, voici pour point de départ deux indicateurs spécifiques :

- le **End-Of-Life Recycling Rate** (EoL RR) est la part de matériaux contenue dans des produits arrivés en fin de vie qui est collectée, prétraitée et finalement recyclée pour être introduite à nouveau dans le cycle. C'est l'indicateur communément appelé « taux de recyclage ».
- le **Recycling Input Rate** (RIR) mesure la part de métal provenant du recyclage dans la totalité de la production de ce métal.

Il convient également de préciser de quelles 'sources' le métal doit être issu pour être considéré comme 'recyclé' : prend-on en compte uniquement les produits en fin de vie, les chutes de métal générées durant les activités de production, etc.

Pour un exemple de modélisation intégrant la notion de recyclage, voir le **projet SURFER** porté par le CNRS, le BRGM et l'ADEME. Cette modélisation permet de mettre en lumière comment le rythme de développement des filières de recyclage peut être un paramètre décisif.

NB : Il est important de noter qu'on ne peut **jamais atteindre un taux de recyclage de 100%**. Cela est dû à des pertes inévitables au moment de la collecte, au niveau des procédés, etc. En effet, une des grandes difficultés du recyclage est qu'un même produit contient de très nombreux éléments chimiques différents (c'est une tendance qui s'accentue). Cette entropie se manifeste également par une perte de qualité progressive du matériau à chaque boucle de recyclage. Le matériau doit être utilisé dans des applications nécessitant un niveau de pureté moindre, et l'application initiale nécessite alors un apport en matériau 'neuf'.

De plus, le recyclage nécessite différents types de procédés (recyclage mécanique, chimique, thermique, …) Cela implique donc une consommation d'énergie et, directement ou indirectement, un rejet de substances dans l'atmosphère ou autre. Ainsi, le recyclage permet dans la grande majorité des cas de réduire l'impact environnemental par rapport à un métal directement extrait de la croûte terrestre, mais **cela ne permet pas de faire disparaitre cet impact pour autant**.

Bibliographie

ADEME. (2017). *L'épuisement des métaux et minéraux : faut-il s'inquiéter ?* (p. 23).

Association négaWatt. (2018). *Scénario négaWatt 2017-2050 : Hypothèses et résultats* (p. 49).

Bonnet, C., Carcanague, S., Hache, E., Seck, G. S., & Simoën, M. (2019). *Vers une géopolitique de l'énergie plus complexe ? Une analyse prospective tridimensionnelle de la transition énergétique* (p. 132).

Bonnet, C., Carcanague, S., Hache, E., Simoen, M., & Seck, G. (2019). *The impact of Future Generation on Cement Demand: An Assessment based on Climate Scenarios*.

Carbone 4. (2019). *Changement climatique et industrie minière - Etude de cas : l'exposition des gisements de terres rares au risque climatique*. Consulté à l'adresse http://www.carbone4.com/wp-content/uploads/2019/02/Publication-Carbone-4-Changement-climatique-et-industrie-miniere.pdf?mc_cid=d4c1f06fc1&mc_eid=bb900a74db

Commission européenne. (2017). *Communication de la commission au parlement européen, au Conseil, au comité économique et social européen et au comité des régions relative à la liste 2017 des matières premières critiques pour l'UE*. Consulté à l'adresse https://ec.europa.eu/transparency/regdoc/rep/1/2017/FR/COM-2017-490-F1-FR-MAIN-PART-1.PDF

Donella H. Meadows, Randers, J., & Meadows, D. L. (2004). *Limits to growth: The 30-Year Update*. Chelsea Green Publishing; 3 edition (June 1, 2004).

Hache, E., Seck, G. S., Simoen, M., Bonnet, C., & Carcanague, S. (2019). Critical raw materials and transportation sector electrification: A detailed bottom-up analysis in world transport. *Applied Energy*, *240*, 6-25. https://doi.org/10.1016/j.apenergy.2019.02.057

IFRI. (2018). *La transition énergétique face au défi des métaux critiques* (p. 56).

Seaman, J. (2019). *Rare Earths and China: A Review of Changing Criticality in the New Economy* (p. 36). IFRI.

United States Department of Energy. (2015). *Quadrennial Technology Review An Assessment Of Energy Technologies And Research Opportunities - Chapter 10: Concepts in Integrated Analysis* (p. 39).

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Employment assessment of energy transition scenarios

Technical file #12 – Draft version

Information and recommendations for scenario producers

This document is part of a set of 12 technical files. These files have been produced by *The Shift Project* after one year and a half of research and experts consultations on the different aspects of energy transition and the future studies around these aspects.

Our project, "Power Systems 2050 – Guidelines for design," started in January 2018, with the participation of 10 experts who defined the key subjects which according to them have to be collectively tackled by future studies about the power transition. *The Shift Project* then investigated each of these subjects, consulting in total 40 experts, organizing 4 workshops, and reviewing a large bibliography, including a dozen of future studies about power (and energy) transition at different geographical scales.

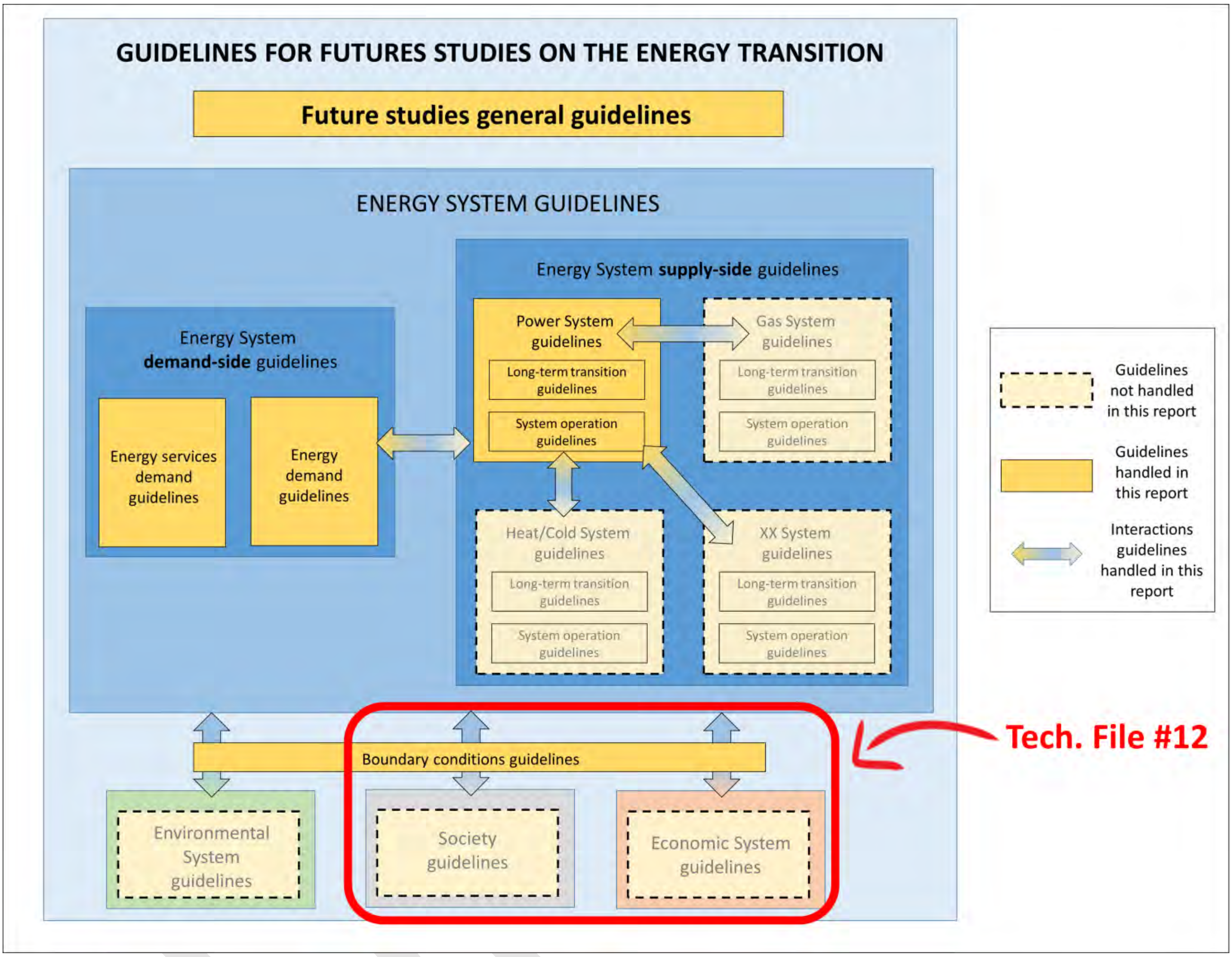
The goal of this project is to produce a set of guidelines addressed to scenario producers. These guidelines seek to foster transparency and consistency *within* future studies and to develop a common language *across* studies. By defining a number of important items which are key to deal with in future studies, we actually propose a study template which enables a better understanding of the location of each proposed scenario on the tree of possible transitions. Once again, the objective is not to *rank* studies, or scenarios, but rather to *compare* them to get a better collective overview of the different aspects of the transition (what are the differences between studies in terms of driving questions, hypotheses, models, methodology, results?).

Several aspects of the energy transition are handled in these technical files. However, on the energy supply-side only the power system has been studied. The main reason for this choice is that we had to start from somewhere with limited resources, and the power system seemed to be a key system to study in the energy transition context, towards a low-carbon economy, as shown by the growing number of future studies focusing on this system. However, the guidelines we propose could be completed by analyzes on the other energy supply-side systems (the gas system, oil system, heat system and so on).

Each technical file tackles several aspects of future studies for the power (and energy) transition. Here is the complete list of the technical files produced during the project:

#	Technical file title
1	Future studies on the energy transition
2	Energy transition models
3	Boundary conditions for energy transition scenarios
4	Long-term evolution of energy consumption in energy transition scenarios
5	Lifestyles and consumption behaviors in energy transition scenarios
6	Long-term evolution of the power system supply-side in energy transition scenarios
7	Power system operation in energy transition scenarios
8	Impact assessment in energy transition scenarios
9	Transition desirability in energy transition scenarios
10	Environmental assessment of energy transition scenarios
11	Economic evaluation of energy transition scenarios
12	Employment assessment of energy transition scenarios

Altogether, these files cover the fields described on the following map of the guidelines for future studies on the energy transition. The document you are reading covers the red-circled topics.



In addition to these technical files, three complementary notes have been produced as specific focuses on the following aspects: material criticality in energy transitions (in French, to be translated and added to technical file #10), levelized cost of electricity (LCOE) in energy transition future studies (in French) and discount rate in energy transition future studies (in French).

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Reading keys

Explanation box, containing key information for a better overall understanding of the subjects.

Recommendations for scenario producers:

These boxes contain the recommendations for scenario producers.

The word "should" means that scenario producers, if they are to follow the guidelines, must substantiate the corresponding point. The words "may" or "might" relates to suggestions, ideas to help the scenario producer respond to the point.

Questions in italic are examples of questions scenario producers might ask to substantiate the points. They are here in an illustration purpose.

Phrases in italic in the text are words which are being defined and will be subsequently used in the framework.

Phrases which are highlighted in yellow refer to other technical documents of this series.

I. Introduction on employment assessment

A. Employment definition and usefullness for public decision

1. A job is a number of worked hours

The definition of what is a "job" is not universal. A job is usually associated with a "working person". But that person could very well be at work 10 hours a day, 6 days a week since the age of 10, or 35 hours a week for 40 years.

It is therefore necessary to clarify what is considered as a "job". The best way to do this is to associate a job with a total number of hours of work, for example by defining a number of hours worked per year with the corresponding number of years required. Using full-time equivalent (FTE) after defining the corresponding workload can be an appropriate approach.

E.g.: building this new section of cycle path requires 3000 hours of work, i.e. 2 FTEs of 1500h/year for 1 year.

Recommendations for scenario producers:

What is called a "job" in the employment assessment should be defined. It should be ultimately expressed as a total number of hours of work, typically by providing a workload per year and a corresponding number of years.

What is the workload of a full-time equivalent job? How many FTE over how many years are required?

2. Job *need* rather than job *impact*

In future studies, employment assessment usually comes after the definition of a pathway. Therefore the term "job impact" is used very often. However in the real world big changes do not come from nowhere and as a result have an impact on employment. Instead, open job positions and skilled workers are needed before these big changes can actually happen. These are prerequisites. This is why we prefer to use the "job need" designation.

3. Employment is a key indicator for political decision makers

Employment is a key indicator for political decision makers if they want to involve people in a strategic choice. Assessing this aspect enables to better prepare the training for people, the infrastructures, training the instructors, for the right economic sectors. Many future studies already assess employment while some other don't.

As pointed out by (Perrier & Quirion, 2017b), although this indicator is less systematically studied than cost indicators, it may have an equivalent importance in the public debate. A policy with a real or perceived negative impact on employment could be disqualified.

This importance given to the employment assessment of scenarios can partly be explained by the high unemployment rates currently experienced in some countries (sometimes for decades), as unemployment can raise strong desirability issues.

4. When talking about employment, human resource management issues are at least as important as the global net employment need

When assessing employment, several indicators are useful to enlighten public debate.

First, the global net employment need is an important value. It makes it possible to compare two scenarios. *Which trajectory has the highest need for employment? Are the two values close or very different?* Stakeholders can then decide which situation they prefer according to whether they prefer more or fewer jobs in the future.

But this is not the only indicator that matters, and not necessarily the most important one.

Indeed, a transition in employment is above all a need in human resource management. Human resource management is required both to handle the need for skills in the case of job creations and for people management in the case of job destructions.

The sectoral distribution of the creation and destruction of jobs, as well as their geographical distribution are key elements to better inform this human resource management. It is this level of details that enables to build a detailed narrative, making it possible to discuss the desirability of the proposed trajectory with the stakeholders.

These different elements will be discussed in this following parts.

Recommendations for scenario producers:

Scenarios should assess the employment needs in their world.

Global net employment need is an interesting indicator, but it should be completed with insights about human resource management evaluation. This concerns both the need for skills in the case of job creations and people management in the case of job destructions. This can be enlighten thanks to an evaluation of sectoral and geographical distribution of the creation and destruction of jobs.

In the end, all these elements should be used to build a comprehensible narrative for stakeholders so as to discuss the enabling conditions and the overall desirability of the proposed trajectory.

B. Introduction on existing employment assessment methods

1. Two literature reviews

(Quirion, 2013) and (Breitschopf, Nathani, & Resch, 2012) are the two main sources presenting a review of existing employment assessment methods used for writing this employment section.

They both explore pros and cons of the several methods they present. (Breitschopf et al., 2012) provides a "methodological guidelines for estimating the employment impacts of using renewable energies for electricity generation" while (Quirion, 2013) provides a review of existing methods, especially those used in future studies, before evaluating the employment need of the study (NégaWatt, 2011).

2. Gross assessment is useful from a specific actor's perspective whereas net assessment is required to enlighten system perspective

As any public policy, energy policies do create jobs in some sectors and destroy jobs in others. Therefore one should first distinguish two main types of employment assessment: gross assessment and net assessment.

A gross assessment focuses on job creation only or on job destruction only while net assessment takes both effects into account.

Assessing a gross effect can sometimes appear as a caveat but it is not. In fact, all depends on the question that is being answered. (Breitschopf et al., 2012)

Indeed, gross effect can be useful from a specific actor's perspective. (Percebois, s. d.) gives the example of a study from AREVA evaluating the destruction of employment related to a nuclear phase-out, and another example of a study from SER assessing job creation in the renewable energy industry related to an increase of RES in the mix. In both cases, this kind of gross assessment provides insights for one specific industry and is therefore useful from this specific industry point of view, both for work unions and business owners of the sector.

However, gross effect alone is not adapted to inform public decision from a system perspective (see Economic Evaluation section for a detailed *system perspective* definition)

Indeed, when estimating the global employment need of a scenario, net assessment is better adapted. (Criqui, 2013; Quirion, 2013)

Therefore we will focus only on net assessment methods in this employment section (just note that not all the net employment assessment methods enable to enlighten system point of view, as explained in the next part).

Recommendations for scenario producers:

Scenario producers should explain their choice of assessing only job creation, only job destruction or both job creation and destruction with regard to the question that is being answered and the related chosen point of view of their employment need assessment.

The answered question and the related chosen perspective should be clarified.

Gross assessment (only job creation or only job destruction) is better adapted from a specific actor's perspective. A net assessment (both job creation and destruction) is required to evaluate the global employment need of a scenario from a system perspective so as to fully inform public decision.

3. Four categories of effects on employment: how deep in the value chain to assess employment need for a transition?

Methods to assess employment needs divide those needs into four main categories.

a. Direct and indirect effects

The first two are direct effect and indirect effect.

Direct jobs are those in the primary industry sector that is mobilized for the proposed transition. It can include jobs in fuel production, manufacturing, construction, and operations and maintenance.

Indirect jobs generally include jobs in secondary industries which supply the primary industry sector. This is all the supply chain and may include, for example, catering and accommodation. (Rutovitz, Dominish, & Downes, 2015).

In other words direct jobs are those in the branches directly solicited for the transition while indirect jobs are those appearing (or disappearing) within the suppliers of this branches, and their own suppliers, etc.

Both effects are of a *technical* nature: they occur within the energy sector and do not involve any macroeconomic mechanism.

b. Induced effects

The third category is induced effects.

These effects on employment are of a macroeconomic nature.

From one study to another, the term "induced effect" often takes on different definitions, and may sometimes not even be clearly defined.[1] Therefore we will refer here to induced effects as all the effects on employment of a macroeconomic nature that can be calculated alone, that is independently of other effects.

One calculated, these effects can added up 'manually' to direct and indirect effects without going through the use of a macroeconomic model ("full model" approach), as detailed later.

We will later explore several examples of studies assessing induced effects. From one study to another, these effects are sometimes similar, sometimes different, or they can partially overlap.[2]

One example of induced effect: the 'expenses-induced' effect

To give an example, (Quirion, 2013) takes into account an induced effect corresponding to the jobs created or destroyed by the change in expenses of all economic agents (households, private actors, the State ...) To remove any ambiguity we will use the "expenses-induced" designation for this type of induced effect. When comparing a transition scenario to a reference scenario, there are two possibilities for these economic agents:

- They can either benefit from cost reductions (e.g. if they consume less energy for heating after insulating of their houses). In that case all the money that is not saved is reused, which increases consumption in other sectors of the economy. This leads to job creation. These jobs are called here expenses-induced jobs.

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[1] "Induced effect" designates for example jobs resulting from spending wages earned in the primary energy industries in (Rutovitz, Dominish, & Downes, 2015), while it refers to all the jobs created or destroyed by any macroeconomic mechanism in (Percebois, s. d.), etc.

[2] This is why we indicate 'some induced jobs' in summary equations and tables.

- Or, they can have to pay for additional costs. It causes the opposite effect: consumption reduces in other sectors which has a negative impact on employment.

Thus, this effect is not technical but rather macroeconomic. Expenses-induced effect can be significant.

c. Other macroeconomic effects

The last effects on employment are all other macroeconomic effects, such as merit order effects, multiplier effect, or effects occurring when economy is close to full employment, or when a policy improves the balance of trade, etc. Some of these macroeconomic feedback loops are detailed later in the model-based methods paragraph.

4. Summary equation and table

Now that these four types of effects are defined we can express the total net employment need with the following equation:

Total net employment need **= Δ direct jobs + Δ indirect jobs + Δ** some **induced jobs + Δ jobs due to other** macroeconomic effects

With Δ = job creation – job destruction (otherwise this would be a gross assessment rather than a net assessment).

Not all employment assessment methods take all these effects into account. As we will see, these methods tends to gradually add effects in their assessment which allows to progressively expand the scope of the branches of the economy taken into account.

Here is a table to visualize and categorize employment assessment methods. Every existing study would probably fall into one of those boxes:

	Direct jobs	Direct + indirect jobs	Direct + indirect + some 'induced' jobs	Direct + indirect + some 'induced' + other macro-related jobs
Job creation or destruction	Gross assessment			
Job creation & destruction	Net assessment			

Source: author

Figure 1: Employment assessment methods summary table #1

Note: no matter the type of future study, none of those we reviewed was evaluating job need of their several scenarios in their core modelling. Indeed, all the studies including an employment assessment within our scope were always requiring an extra evaluation to do it: a modelling of the Institute for Sustainable Futures at the University of Technology Sydney for (Greenpeace, 2015), (Quirion, 2013) study for (NégaWatt, 2011), the use of ThreeMe model for (ADEME, 2012), (Cambridge Econometrics, 2011) modelling to evaluate (European Commission, 2011), etc.

Furthermore, there is no direct link *a priori* between the type of future study and the chosen employment assessment method.

Several methods to perform a net employment assessment are presented in the next part.

II. The four main types of net employment assessment methods

In this part, four types of methods for net employment assessment are presented.

	Direct jobs	Direct + indirect jobs	Direct + indirect + some 'induced' jobs	Direct + indirect + some 'induced' + other macro-related jobs
Job creation or destruction				
Job creation & destruction	1	2	3	4

These methods exist along a continuum: the further to the right of the table, the more effects are taken into account, but the more complex the evaluation becomes. The last column for example enables to take all effects into account but requires the use of macroeconomic models which are difficult to grasp.

'Manual' vs Full-model approaches

A first distinction between these methods comes from the way in which the calculations are carried out.

Columns 1, 2 and 3 follow a 'manual' process, where the employment need for each sector is calculated thanks to employment factors and where the effects can be calculated separately (as in column 3 where induced effects are calculated separately from direct and indirect effects).

Column 4 consists in the use of a macroeconomic model. This type of method is called here 'full-model' approach.

There is therefore a trade-off between clarity and completeness. On the one hand, full-model approach takes all macroeconomic effects into account. On the other hand, manual methods have the advantage of being inherently transparent and relatively simple to understand. Main drivers of the results are typically more easily identified with such method. It makes it easier to build a narrative around the transition in employment, and thus facilitate discussion with stakeholders. Manual methods can be grasped more easily and can therefore be transparently reused for more disaggregated evaluations such as employment need assessment of a transition on a local scale for example, as with the tool (« Outil TETE - Transition Ecologique Territoires Emplois », s. d.)

Technical vs Macroeconomic approaches

Another distinction between these methods lies in the scope of the considered branches of the economy. Each effect is indeed linked to corresponding branches of the economy.

The first column provides insights on branches directly linked to the transition. The second column takes in addition all the involved supply chain branches into account. These two types of methods are called **'technical'** because they focus on the energy sector only by excluding any macroeconomic effects (as explained in the previous part, direct and indirect effects are of a technical nature). Since macroeconomic effects are often significant, we argue technical methods alone are not suitable for fully informing the debate on total employment need from a system perspective.

Rather, technical methods are useful to provide insights for a set of specific actors. Unlike gross employment assessment, they make it possible to shed light on both the job creation and job destruction, and thus inform more broadly the various specific actors' perspectives. A dedicated narrative can enable to enlighten the related human resource management needs.

Unlike technical methods, the third and fourth columns also assess the employment needs in other branches of the economy. These are so-called '**macroeconomic**' approaches, whether the method is 'manual' (column 3) or 'full-model' (column 4). Since macroeconomic effects are often significant, we argue macroeconomic methods are the only type of approach that can inform the debate on total employment need from a system perspective.

Here is the corresponding summary table:

	Technical		Macroeconomic	
	Manual			Full-model
	Direct jobs	**Direct + indirect jobs**	**Direct + indirect + some 'induced' jobs**	**Direct + indirect + some 'induced'+ other macro-related jobs**
Job creation or destruction ***(gross assessment)***				
Job creation & destruction ***(net assessment)***	1	2	3	4
	Branches directly involved in the transition	+ all the supply chain branches	+ other branches of the economy	

Considered branches of the economy

Specific actor perspective (one sector or one group of sectors such as REN sectors)

Multiple specific actors perspectives (many sectors)

Society perspective

Source: author

Figure 2: Employment assessment methods summary table #2

Each method also has other specific advantages and caveats, which will be explored in the next section. For example, they all enlighten sectoral distribution of job creation and destruction but not with the same disaggregation level. Sectoral distribution is crucial information with regards to human resource management so as to inform the debate with stakeholders.

A. Two technical types of methods to enlighten multiple specific actors' perspectives

This part provides a description and discussion about the two technical types of employment assessment methods. The first one takes only direct jobs into account while the second one considers both direct and indirect jobs.

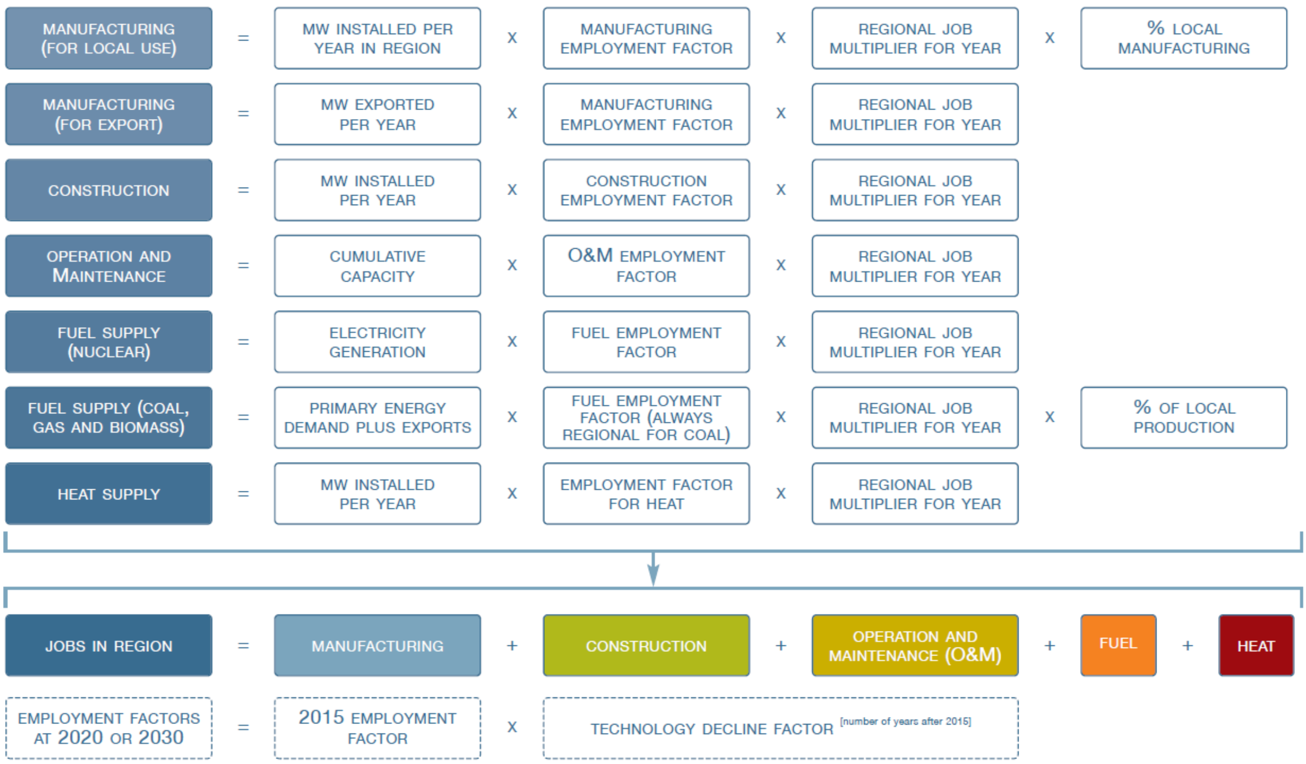
1. Assessing branches directly involved: a type of method to evaluate net direct employment needs

The first method is a technical and manual one, focusing on direct employment only. The related equation would be:

Net employment need **= Δ direct jobs**

a. A method based on 'physical' employment factors

This is an approach used in studies such as (Greenpeace, 2015) and (Lappeenranta University of Technology / Energy Watch Group, 2017). They both explain the several steps of their employment assessment. The method behind these two assessments is described in details in (Rutovitz et al., 2015), and summed up by (Greenpeace, 2015) with the following figure:



Source: (Greenpeace, 2015)

Figure 3: Overview of the net direct employment assessment method from (Rutovitz et al., 2015)

Jobs are divided into seven branches: manufacturing for local use, manufacturing for exports, construction, operation and maintenance, nuclear fuel supply, coal, gas, and biomass fuel supply, and heat supply.

For each branch there is a physical need derived from the scenario: MW installed each year for manufacturing, energy demand each year expressed in PJ for fuel supply, etc.

Each physical quantity is multiplied by a job factor, expressed as jobs/MW or jobs/PJ. In order to distinguish this type of employment factors from those expressed in jobs/€ (see next method), we will call them **'physical'** employment factors.

Since these physical job factors are calculated for OECD countries, a regional adjustment is applied where a local factor is not available thanks to a "regional job multiplier". Furthermore, each physical job factor is also time-adjusted thanks to a "technology decline factor" that reflects the increase in productivity over time. Indeed, as technologies and companies become more efficient and production processes are scaled up, the employment content of an activity progressively decreases.

Finally, the results for the seven branches are added together to obtain the final result.

As explained in (Rutovitz et al., 2015), there are still some significant areas of employment which are not included in the evaluation such as jobs in periodic replacements of the plants, jobs in energy efficiency, and a portion of the jobs related to heat supply. This is a transparent limitation specific to this study.

More generally, most of the work of such methodology lies in estimating the physical employment factors. As explained in the Limitations section, this can be a complicated task.

Note: this method can also be used for gross assessments such as the estimation of direct job creation need only. (Breitschopf et al., 2012) describes how to perform a gross assessment with this method. This is what they call "Employment factor approach". Further information can be found in (Breitschopf et al., 2012).

b. Limitations: no indirect jobs and no clear separation between direct and indirect jobs at the same time

The first obvious limitation of this type of method is that **it doesn't take into account indirect effects**. These are not negligible: as mentioned in (Rutovitz et al., 2015), "The inclusion of indirect jobs would typically increase job numbers by 50 – 100%." It can be noted that the study is transparent on this limitation, which is a good practice.

The second limitation of this approach lies in the way physical employment factors are determined. As (Breitschopf et al., 2012) explains it: "there are only a few basic data sources that are used to derive job factors, and the job factors for the same technologies vary greatly between the sources. In many cases, the employment factors are poorly documented, so that definitions of the system boundaries of technologies are not always transparent." Results could be very different between two studies using different databases.

(Rutovitz et al., 2015) confirms that a large number of assumptions are required to make the calculations. Indeed, "Quantitative data on present employment based on actual surveys is difficult to obtain, so it is not possible to calibrate the methodology against time series data, or even against current data in many regions".

This is related to the fact that there is no clear separation between direct and indirect jobs. This blurred lines result in an uncertainty range for the physical employment factors values for each sector. Therefore, final results could be strongly biased upwards or downwards.

NB: we could also mention as a third limitation the static nature of physical employment factors. This limitation is rather developed for the next type of method.

Recommendations for scenario producers:

When evaluating net direct employment needs only, it should be explicitly mentioned that such assessment only enlightens employment needs of branches directly involved by proposed changes of the scenario. Indeed, all the related supply chain branches are not taken into account.

Such a choice of method should be justified with regards to the driving question.

In addition, scenario producers should provide discussion about the uncertainty around the physical employment factors values, especially about the fact that for each sector the distinction between direct and indirect jobs is often unclear. The static nature of physical employment factors should also be discussed.

2. Assessing both branches directly involved and the related supply chain branches: a type of method to evaluate net direct & indirect employment needs

As the previously presented method, this type of approach is also both technical and manual. It enables to consider both direct and indirect effects. The related equation would be:

Net employment need = Δ direct employment + Δ indirect employment

a. A method based on 'monetary' employment factors determined through an Input-Output analysis

The following steps are described in line with explanations presented in (Quirion, 2013).

As with the previous method, different branches are defined and a physical need is derived from the scenario for each branch (let's take the example of MW of installed wind turbines).

Then, a unit cost is calculated for each branch (these would be the €/MW value of installed wind turbines). This unit cost can vary over the time to reflect changes in costs in each branch during the scenario timeframe. Compared to previously presented method, additional information is required to evaluate these unit costs.

The multiplication of physical need and the corresponding unit cost gives a monetary demand associated with each activity (total amount of € for wind turbine installation).

Each monetary demand is then multiplied by a job factor, expressed as **jobs/€**, which will be called here **'monetary' employment factors** in order to distinguish it from physical employment factors (see previous method). The monetary employment factor of each branch is estimated by an input-output analysis, which makes it possible to count the jobs related to all intermediate consumption. Indeed, cost implicitly integrates the entire value chain and therefore both branches directly involved and the related supply branches. This is the advantage of using monetary employment factors: they enable to take both direct and indirect jobs into account.

This results in the net job needs associated with each branch. All the branches can be added together to obtain the total net result.

This calculation is carried out twice: once for a reference scenario and once for the assessed scenario. Employment need is therefore expressed as the difference between the outcomes for the two scenarios.

This is the method used in (« Outil TETE - Transition Ecologique Territoires Emplois », s. d.) for example.

An advantage of this type of method is the possibility of taking into account a large number of sectors. This enables a wide range of choices in the way results are presented. Indeed, the results for these numerous sectors can be merged in many ways to provide useful information. This sectoral disaggregation thus makes it possible to build very specific narratives so as to better enlighten public debate and the discussion with stakeholders.

Note: as for the previous method, this method can probably also be used for a gross assessment. (Breitschopf et al., 2012) presents a similar method (with a few differences) they call 'Gross Input-Output modelling', for gross assessment. They describe the several assessment steps in detail, with concrete examples. Further information can be found in (Breitschopf et al., 2012).

b. Limitation: the static nature of this method implies additional work and assumptions to make it more dynamic

The main limitation of this approach when applied to future studies is its static nature due to the use of an input-output matrix.[3]

Indeed, this matrix reflects the current functioning of the economy. Thus, keeping the values contained in the input-output matrix fixed would consist in assuming everything goes as if the economy didn't change during the scenario. This remains true as long as the studied system remains relatively similar to today's system; however it is not necessarily the case.

Simulating an evolution of the functioning of the economy in accordance with the changes happening within the studied scenarios requires the integration of several phenomena. However integrating all these elements would represent a considerable amount of work, which naturally leads to simplification assumptions.

Here are three of the main elements that can be made dynamic so as to make the structure of the economy of an input-output matrix evolve[4]:

- Changes in productivity. Indeed, as previously explained, employment content of an activity progressively decreases when productivity increases. This parameter should logically be distinguished for each branch and its evolution should depend on changes occurring in each scenario. However, productivity is a complicated parameter to measure. Therefore, there is often a single value for all branches, which is also not distinguished between reference scenario and assessed scenario. In that case, it means productivity is considered exogenous (indeed no matter the changes occurring within the pathways, productivity would evolve in the same way, which means that "something else" outside the scenarios is responsible for the productivity evolution).

- Intermediary goods prices such as energy and raw material prices. Indeed, if oil price increases, monetary employment factors (jobs/€) of branches related to oil activity decreases. Similarly, if the price of certain raw materials increases, then the employment content related to certain renewable energy branches would decrease for the same reason.

- Imports-exports situation evolution within single branches. If part of a branch is offshored, then its monetary employment factor evolves. This is another type of change within the scenarios timeframes that requires additional work to be integrated into the input-output matrix. Changes in monetary employment factors values typically depend on assumptions about the locality of employment. Indeed, job

[3] The previously presented method is also of a static nature.

[4] The first and the third elements (change in productivity and imports-exports situation evolution) can also make physical employment factors more dynamic.

content varies differently depending on whether the job is created locally or not (see Regional evaluation paragraph).

NB: Integrating these changes without transparency and a narrative to explain the causes of these changes would bring opacity to the results and would be counterproductive.

Recommendations for scenario producers:

When using input-output analysis for employment assessment, the static nature of the simulated economy should be discussed.

Is the input-output matrix modified according to changes in productivity along the scenario? Or changes in imports-exports situation? Or changes in intermediary goods prices?

If such changes are taken into account or if monetary employment factors do not evolve, this should be justified with a corresponding narrative in any case. Assumptions about the locality of employment are also important to that extent since it can impact job content greatly.

Why productivity would increase faster in the assessed scenario compared to the reference scenario? Why value would differ from one branch to another? How is job content affected in my scenario after a change in oil prices depending on the country where job destructions or creations happened?

3. Discussions about technical methods

As previously explained, the two types of methods presented here are both technical (since no macroeconomic effect is taken into account) and manual (since they do not require the use of a macroeconomic model).

Both types of methods first start the calculation with the physical flows of each considered branch and then uses employment factors.

The first approach uses physical employment factors and can be summarized by "jobs = MW(h) * jobs/MW(h)". The second approach uses monetary employment factors and can be summarized by "jobs = MW(h) * €/MW(h) * jobs/€".

Because these are manual methods, they are more transparent by nature, which enables better discussion with stakeholders. However, each method has its own limitations, particularly on the values of employment factors.

Because they are technical methods, only the branches directly involved in the transition (first approach) and the supply-related branches (second approach) are taken into account. Therefore these methods can enlighten multiple specific **actors' perspective**s.

However all other branches of the economy are not included within their scopes. This would be a major limitation for the estimation of the total net job need of a scenario from a system perspective. Several sources (Breitschopf et al., 2012; Criqui, 2013; Quirion, 2013) seem to share this vision. Technical methods have for example a cost bias favoring expensive solutions since they do not assess expenses-induced jobs. Indeed, as explained in (Quirion, 2013): "as Huntington (2009) points out, the most costly technical and organizational options typically create more jobs per unit of energy than the others, but their extra cost will necessarily be paid by economic agents who will consequently reduce other expenses, leading to a drop in activity and to a negative "induced" effect on employment."

In a nutshell, these methods are suitable for enlightening multiple specific actors' perspectives but not system perspective.

Recommendations for scenario producers:

Technical methods provide useful insights about job transition from multiple specific **actors' perspective**s. A dedicated narrative should be provided to that extent to enable discussion with stakeholders, for instance by enlightening the human resource management needs related to the assessed job transition. As technical methods are also manual methods, transparency is more easily achieved.

Furthermore, technical methods are not truly adapted for estimating the total net job need of a scenario from a system perspective. Macroeconomic methods should be preferred for that purpose. If a technical method is however used for that purpose, an explanation of the extent of the limitation with regards to the answered question should be added.

B. Two macroeconomic types of methods to enlighten system perspective

This part provides a description and discussion about the two macroeconomic types of employment assessment methods. The first approach is a manual one and takes direct, indirect and some induced jobs into account while the second one is a full-model approach and considers all effects.

1. **Assessing 'technical' branches and some other branches of the** economy: a manual type of method to evaluate net direct, indirect and some induced employment needs

This type of approach is macroeconomic and manual: it enables to manually take some macroeconomic effects into account. These are called induced effects. The related equation would be:

Net employment need = Δ direct employment + Δ indirect employment + Δ some induced employment

Recommendations for scenario producers:

Since the meaning of "induced effect" varies from one study to another, a clear explanation of what is actually assessed should be provided whenever an "induced effect" is calculated.

a. Two methods based on input-output analysis

The two methods that will be presented here calculate separately direct and indirect effects on the one hand and one or more types of induced effects on the other hand before adding them together. They also both use input-output analysis.

(Quirion, 2013) method

This first method is described and applied to (NégaWatt, 2011) study in (Quirion, 2013).

Firstly, direct and indirect effects are calculated thanks to the previously presented approach, using monetary employment factors determined with an input-output matrix (see corresponding part).

Secondly, an expenses-induced effect is calculated. As explained in Induced effects paragraph (see 'Four categories of effects on employment' section), expenses-induced jobs are the jobs created or destroyed by the change in expenses of all economic agents: if they benefit from cost reductions, money that is not saved is reused, which increases consumption in other sectors of the economy. This leads to job creation. If they have to pay for additional costs it is opposite and it leads to job destruction. Expenses-induced effect can be significant.

Calculating this effect requires further hypothesis: *which economic actors will support the extra costs, how will they change their savings and consumption in response to these extra costs?* (Quirion, 2013) assumes that cost variation goes to households and that they consequently change their consumption by the same amount and with a distribution similar to their initial consumption.

In this case, calculating expenses-induced effect consists in estimating the variation in the amount of household expenditure on the one hand and the average employment content created by household consumption on the other hand, before multiplying the two values. See (Quirion, 2013) for more insights and for the application of this method to a future study.

(Breitschopf et al., 2012) **"Net** Input-Output **modelling" method**

This corresponds to one of the four methods presented in the (Breitschopf et al., 2012) methodological guidelines. It requires the use of two types of input-output matrix: a *quantity* IO model and a *price* IO model.

After estimating direct and indirect effects with the quantity input-output model, this method estimates two types of induced effects:

- The first one corresponds to the changes in household income due to employment in concerned industries. It is estimated with the same quantity input-output model. This type of induced effect is not taken into account by (Quirion, 2013) method.

- The second one corresponds to the changes in electricity prices caused by the switch to a new electricity mix. The price changes are borne by electricity consumers and affect consumption and other production industries. It is estimated with the price input-output model. This induced effect is a portion of the previously presented expenses-induced effect.

Many more insights (detailed calculation steps, data requirements, discussions, etc.) can be found in (Breitschopf et al., 2012).

As they are based on input-output analysis, an advantage of this type of method is the possibility of taking into account a large number of sectors. As explained previously, this enables to build very specific narratives so as to better enlighten public debate and the discussion with stakeholders (see corresponding paragraph).

b. Limitations: some missing effects and a static nature

A first limitation of such approaches is intrinsic to every non 100% technical method: additional assumptions of a macroeconomic nature has to be added. For example, in (Quirion, 2013): *Which economic actors will support the extra costs, how will they change their savings and consumption in response to these extra costs?*

A second obvious limitation is that other macroeconomic effects are not taken into account, such as feedback loops and interactions between actors, prices, quantities and markets (Breitschopf et al., 2012). Adding them one by one 'manually' would probably be a far too complex exercise. This is why the only way to take all these effects into account is to use a full model-based approach.

Therefore (Quirion, 2013) provides qualitative evaluation and discussion about the magnitude of some neglected macroeconomic effects. It concludes that some of these main missing effects ('full employment' effect and 'elastic' effect on balance of trade balance) should be small given the context of the study (high unemployment and European context), and that the main drivers of the results would remain the same.

Further considerations on the magnitude of these neglected effects are presented in the 'Discussions about macroeconomic' section.

Recommendations for scenario producers:

When using a macroeconomic manual approach, both macroeconomic assumption and magnitude of neglected macroeconomic effects should be discussed.

The third limitation comes from the method used to determine direct and indirect effects. As previously explained methods using input-output matrix are of a static nature and imply additional work and assumptions to make it more dynamic (see corresponding paragraph for more details and corresponding recommendations).

Therefore (Breitschopf et al., 2012) study explains Net Input-Output modelling method loses part of its accuracy when applied to depict future effects, compared to a present effects analysis.

2. Assessing all branches of the economy: full model approaches

This type of approach enables to take all macroeconomic effects into account. The related equation would be:

Net employment need **= Δ direct jobs + Δ indirect jobs + Δ some induced jobs + Δ jobs due** to other macroeconomic effects

a. Three types of model

This kind of assessment is used to evaluate the employment need of future studies such as (ADEME, 2012) though the use of ThreeME model, or (European Commission, 2011) that relies on (Cambridge Econometrics, 2011) to evaluate the net employment effects of the EU's 20-20-20 targets, based on Cambridge Econometrics' E3ME model.

Note: we have not studied this type of method in depth. Other sources such as (Breitschopf et al., 2012) already provide many useful insights. What is presented below is directly based on this source.

There are three main types of model-based methods: macro-econometric models, general equilibrium models, and system dynamics based models. Each type has its own characteristics:

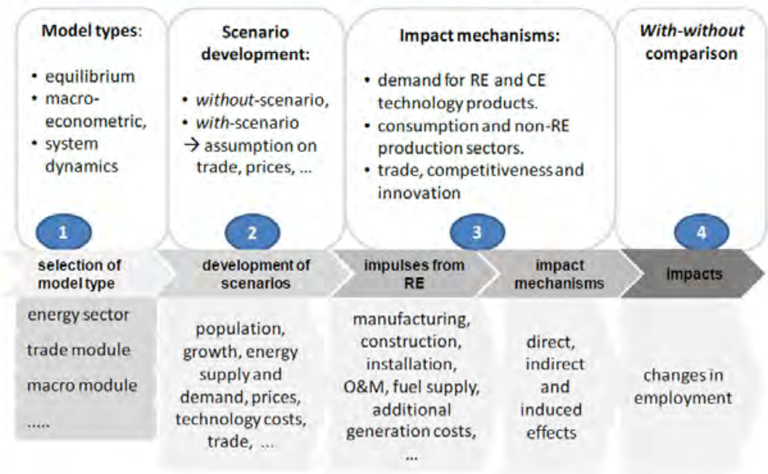
Table 5-4: Overview of model types and their general characteristics

	Macro-econometric model	(Computable) general equilibrium model	System dynamics based model
Use/ Application	Predicts overall level of economic activity (using macroeconomic figures). Analyses transitional impacts e.g. employment, ...	Examines impact of changes in relative prices on economic outcome.	Analyses impacts of price or demand changes on economic activities.
Time horizon	Short- to medium-term predictions	Long-term predictions	Long-term analyses
Drivers	Changes in aggregated quantities, prices	Changes in prices	Changes in prices, quantities
Methods	Considers and solves behavioural and definition equations simultaneously. IO table and national accounting included.	Strong microeconomic foundation with (partial) market equilibriums. Supply and demand functions. CES production and utility function. Contains IO tables.	Consists of non-linear differential equations. Uses positive and negative feedback loops. Includes IO tables and national accounting. Contains attributes of econometric models and applies equilibrium approaches as well.
Parameters	Estimation based on historical data –> fixed relations –> non-optimisation of individual behaviour	Calibrated = replicates data of base year	Estimation and calibration
Crucial issues	Macroeconomic data availability. Time series data. Specification of functional forms.	Exogenous parameters	Complexity
Weaknesses	Great effort involved in model specification. Simplistic functional forms may lead to inconsistencies.	Slightly more emphasis on negative effects since increases in efficiency are hardly taken into account. In some approaches, economic aspects outside the defined field of analysis are kept constant (partial analysis). Assumes optimisation behaviour of economic agents and efficient markets which is not realistic.	Mixed theoretical foundation. Complex structures due to manifold feedback loops
Applicability to net employment impact assessment	Tends to assess effects slightly less pessimistically than equilibrium models. Suited for short-medium term analyses. Depiction of encompassing macroeconomic effects. Depiction of transitional	Depiction of long-term aspects. Depiction of a particular market or a few sectors without including significant spill-overs.	Integration of several sectors and fields of RE use (transportation, heat, power)

Source: (Breitschopf et al., 2012)

(Breitschopf et al., 2012) explores in detail this kind of model-based methods. General procedure of such approach is explained and summed up in this sketch:

Figure 5-2: General procedure in a net impact study



Source: (Breitschopf et al., 2012)

Data requirement is also explored, as a large amount of data is necessary and assumptions need to be made:

Table 5-6: Selection of data required for an economic impact assessment

Data	Unit	Sources
Prices and allocation: Crude oil CO_2 Gas for households, industry, ... Electricity for households, industry, ... Fuel for households, industry, transportation	€ / ... e.g. bbl t kWh kWh l	IEA energy outlook; OECD
Socio-economic data: Population per age group Birth, mortality rate, migration Private households GDP Production value Number of passengers, commercial vehicles, Transportation of goods and persons	 # # € € #; km	National statistics on population, energy, ...
Efficiency indicators: Primary energy consumption (PEC) Share in PEC of each energy source GDP per PEC Final energy consumption (FEC) per household Gross value added per FEC for industry Production value per FEC Transportation per FEC	 GJ/capita % €/GJ GJ/# €/GJ €/GJ km/GJ	National statistics; European Statistics: Eurostat, ...
Emissions: GHG emission factors Substitution factors	 G/kwh %	National statistics, publications of national ministries (environmental, commerce, ...), UNFCCC communications
Policies: Social insurance Tax rates, depreciation rates Operating terms of nuclear power plants, ...		Publications by government ministries; OECD reports
Macroeconomic data: Input-output coefficients National accounting Trade data Labour force data (quantity and qualification)		National and supranational statistics, e.g. Eurostat, UN Comtrade, national energy balance, ...
Statistics on: Housing: real estate prices, existing and new construction, ... Transportation: # of cars, fuel input, average transportation, ... Energy: primary and final energy use, ...		National and supranational statistics, e.g. Eurostat, UN Comtrade, national energy balance, ...

Source: (Breitschopf et al., 2012)

Further insights can be found in (Breitschopf et al., 2012).

b. Some examples of macroeconomic effects

Here are some of the main macroeconomic feedback loops that model-based methods enable to take into account (Breitschopf et al., 2012; Quirion, 2013):

- *Full employment* effect. If the economy is close to full employment, a policy that increases the demand for labor will push up wages. If firms consequently lose market shares and / or substitute capital for work this may reduce the initial positive effect on employment by reducing employment elsewhere in the economy.

- *Elastic* effect on balance of trade. After a policy improving trade balance, some mechanisms - especially though exchange rates - can bring the balance back to equilibrium. This also reduces the initial positive effect on employment.

- *Merit order* effect. If electricity price on wholesale markets is set with a merit order mechanism, a policy increasing the share of renewable energy sources would cause a decrease in the power price due to a higher supply of electricity from sources with low marginal costs (shift of the supply curve to the right). And as any price variation would affect household expenses and industry competitiveness, this would have an impact on employment need.

CO2 price effect, crowding-out effect and multiplier effect are other feedback loops that could be named.

c. Limitations : complexity, less detailed sectoral desaggregation and biases of the chosen economic theory

The first limitation of model-based methods is their complexity.

Using such methods implies a greater need for data and know-how, and therefore a higher budget. This complexity also results in a higher difficulty to identify the main drivers of the results. Indeed, even if a transparent explanation of the model is provided, too many mechanisms are involved to enable a quick comprehension of the overall dynamic. This complicates the debate with the stakeholders.

The second limitation is that these models do not offer the possibility of taking into account a large number of sectors.

In these models, the productive sector is represented by a maximum of about fifteen sectors, compared to 118 in the analysis presented in (Quirion, 2013). Key information can be lost with to aggregated sectors: for example, if jobs in gas and electricity are gathered in the same sector, job evolutions in the case of an evolving share between gas and electricity cannot be properly performed and disclosed. This makes the construction of specific narratives more complicated or impossible and complicates the debate with the stakeholders.

Recommendations for scenario producers:

Due to their complexity and low sectoral disaggregation, full model methods are not naturally adapted to create transparency and clear narratives that stakeholders can grasp so as to create a debate.

Thus, when a full model method is used, scenario producer should put a special effort into building a comprehensive narrative to illustrate the results provided.

What are the main drivers of the results? What do the provided results mean for the different stakeholders?

The third limitation is that the chosen model is subject to the biases of the chosen economic theory. Indeed, there are fundamental differences from one economic theory to another. Results on employment can therefore potentially be significantly impacted by the choice of model.

Recommendations for scenario producers:

When a full model method is used, scenario producer should discuss the extent to which the choice of economic theory can impact the results of the employment assessment.

3. Discussion about macroeconomic methods

The two types of methods presented in this section enable to inform system perspective.

The first type of method is manual, and uses an input-output analysis to calculate direct and indirect effects on the one hand, and then one or more induced effects on the other hand. This type of method offers the possibility of a large sectoral disaggregation, and is naturally transparent. However its static nature implies additional work and assumptions to make it more dynamic and it does not take into account all macroeconomic effects.

The second type of method is composed of full model approaches that make it possible to take into account all the effects dynamically. However it is a complex, prone to ideological biases, approach (difficulties to identify the main drivers of the results) with a relatively low sectoral disaggregation.

There is therefore a trade-off between clarity and completeness.

As already recommended, if the first type of approach is chosen, an effort should be made to explain the assumptions and limitations related to the static nature of input-out matrix and the magnitude of the neglected macroeconomic effects. If it is rather the second type of approach, then the effort should be put into making the results clear, transparent and accessible for stakeholders.

(Perrier & Quirion, 2017a) provides to that extent useful insights by comparing input-output approach and full model approach. Three effects are tested both with an IO model and a computable general equilibrium model (full model approach): labour share, wages and trade. A quantitative employment assessment analysis is then performed with the same data using the two types of model. Some discrepancies do appear even if there is no major inconsistency in the results. Reasons for divergence between the two models are then discussed.

(Breitschopf et al., 2012) provides a table comparing the main characteristics of net Input-Output modelling and full economic model approaches:

Table 2-3: Comparison of the two approaches

Characteristics	Net IO model	Full economic model
Profoundness and accuracy of results	Potentially medium – high. Depending on the level of detail of IO model and update status of IO coefficients	Potentially very high. Depending on the quality of the economic model, update status of IO coefficients and all other relevant data
Direct (RE industry) and indirect effects (RE upstream industry)	Yes	Yes
Induced effects (every sector of the economy)	Type 1 and 2, but limited to consumption (see Annex 1, A 1.3)	Type 1 and 2 Also: could take into account merit order effect, CO_2 prices, crowding-out of investments
Exports, imports	Yes – as a share of sector output or sectoral input	Yes – as share of sector output or input, trade module, etc.
Resource requirements (financial and human)	Medium - high	Very high
Data and model requirements	Medium RE capacity and generation data; technology-specific costs and cost structures; input-output model and coefficients	High RE capacity and generation data; technology-specific costs and cost structures; input-output coefficient, other economic, energy sector-specific and demographic data, macro model with trade module, energy sector module, etc.
Time horizon	Present(– future: simple assessment)	Future[6]
Scenario	Yes (limited baseline or counterfactual)	Yes (baseline)
Dynamic	Limited	Feedback loops, multiplier and accelerator, (endogenous) technical change.
Price and quantity changes	Limited Changes in prices or quantity are completely passed through to total output. Change is based on average coefficients	Yes Price or quantity changes are a result of output and price changes. Changes due to merit-order effect or CO_2 prices can be depicted
Economic relations	--> input-output relations between industry, final demand	--> input-output relations, national accounting, trade, job market, fis-
	payment sector (linear - limitational)	cal, climate, energy sector, household consumption, policies, etc.

Source: (Breitschopf et al., 2012)

They also propose to choose between the two types of methods according to budget availability, human resource, know-how and data availability. They recommend the net IO modelling if these are "limited", and the full economic model approach if these are "sufficient".

C. Additional cross-cutting elements to enlighten discussion with stakeholders

1. Geographical repartition of job creation and destruction

As well as sectoral repartition of job creation and destruction, geographical repartition is another key element since all regions do not undergo the same employment transitions, especially in scenarios with high shares of locally produced energy. This enables to better inform human resource management needs and can raise acceptability issues.

a. Several possibilities for a regional evaluation

Unlike sectoral disaggregation, none of the presented methods seem to directly allow a geographical distribution evaluation of job creation and destruction. Therefore such evaluation is less systematically performed. However, there are several possibilities to inform this aspect of an employment transition.

The most obvious one is to apply the chosen employment assessment several times, for every given geographical region. This is for example performed by (Greenpeace, 2015). The study indeed applies their net direct employment assessment method for ten different regions of the world.

Another possibility to illustrate this regional distribution is to define how the main sectors are distributed across the different regions. Thus, by identifying the sectors that will be strongly impacted by the transition to employment, it makes it possible to visualize which regions will be consequently impacted. This is performed for example in (European Commission, 2018).

In all cases, a qualitative narrative can enable to better illustrate this regional distribution aspect of the transition to employment.

b. Relocatable and non-relocatable jobs

Some jobs cannot be outsourced, such as installation jobs. For these non-relocatable jobs, the question is to figure out how to respond to the human resource needs presented in the next section, within the given geographical area.

Other jobs are relocatable. In this case, responding to the human resource need is less restrictive because it becomes possible to call on skilled workers in other regions or outside the studied geographical scope.

However, relocations may raise desirability issues. As described in (IRENA, 2018): "The geographic distribution of energy sector jobs gained and lost are unlikely to be aligned. This could introduce challenges for maintaining employment among fossil fuel workers if the focus is only put on retraining within the energy sector. […] Additional measures such as social protection programs and adequate transition support are critical." (also see section on desirability)

Furthermore a relocatable job can be effectively outsourced or can stay local.

This depends on several elements:

- The presence or absence of local skills and local industry.

- Competitiveness of the local industry. (Percebois, s. d.) In a globalized world, price has a great influence on relocation choices: if the same good can be produced in a cheaper way elsewhere, relocation is often considered as a consistent option. This depends in particular on the capacity of the given region to take and keep a lead in the concerned sectors. (ECF, 2010). This ultimately requires to correctly manage skills need over time to avoid "bottlenecks" for example. (CEDD, 2013)

- Political choices. Politics can influence the two previous points through subsidies, taxes, bans and obligations and so on, or they can directly decide that no relocations are allowed for example. This depends on the choices made in the scenario.

The fact that a relocatable job is effectively outsourced or stays local has consequences on job content and balance of trade: developing a sector locally leads indeed to local job creations and tends to increase exports while developing it elsewhere does not lead to local job creation and tends to increase imports.

Recommendations for scenario producers:

Scenario producers should substantiate their assessment strategy about the regional distribution of employment needs of their scenarios, with regards to their driving question. If an assessment is performed it should be associated to a specific narrative.

Which regions will be most strongly impacted by the transition to employment? To what extent?

For relocatable jobs, the causes and consequences of offshoring dynamics should be explored.

Are the required skills developing fast enough in the given region so that no imports are necessary? How do relocations impact the employment content of sectors and the trade balance?

2. Job content dynamic

Employment content can vary greatly from one sector to another. This can have a strong overall impact on the employment need of a pathway. Typically, economic activities that come with transition pathways (energy efficiency, RES, etc.) are usually more job intensive than current energy activities (oil, gas and coal, etc.)

In addition, the employment content of each sector also changes over time.

As shown through the description of these several employment assessment methods, the job content of the different sectors vary over time according to many parameters: evolution of productivity, changes in energy and raw material prices, locality of employment, etc.

Recommendations for scenario producers:

The job content of each sector is different, and evolves during the timeframe scenario. Thus, the dynamics of the employment content of the several sectors considered should be explained, with a clear narrative to illustrate discrepancies and evolutions of these values, and their influence on the main results of the employment assessment.

This recommendation has already been formulated for manual methods but also applies for full model methods.

What are the most employment-intensive sectors? How do some changes observed within the scenario timeframe impact the job content values over time? To what extent do these trends influence total employment need?

III. Human ressource management

Transition changes described by scenarios both lead to decline in some sectors and to job creations in other sectors.

Therefore new amounts of skilled labor force are needed for jobs to be created as well as management of people losing their job is required for the change to actually happen without desirability struggles.

As we will see these are key enabling conditions.

A. Skills management for job creation

1. Job need is skills need

We previously explained why 'job need' term could be preferred over 'job impact'. One other added-value of this designation is that it becomes more obvious skills requirement underlies every transition since job need appeals for skills need and more generally for industry experience (which includes the experience in engineering, production or manufacturing).

As (IRENA, 2018) explains it, meeting the human resource requirements of sectors in rapid expansion is an enabling condition for a job transition. It requires to consider education and training policies to meet the demand for the skills needs of these sectors.

Indeed, (CEDD, 2013) supports the fact that paying attention to the supply of work and skills is necessary to avoid "bottlenecks". (European Commission, 2011) also insist on this idea: education and training need to be addressed at an early stage in order to avoid unemployment in some sectors and labour shortages in others. Change rates for each concerned industry in specific country / region is indeed a key element.

Employment needs management also depends on the age pyramid of the concerned population. For example, it is more complicated to mobilize a skilled workforce in a country where a majority of the population is no longer of working age than in a country with a majority of young people.

These questions of taking into account the actual transitions requirement in the labor markets are not only qualitative elements as showed in (Guivarch, 2011): introducing "rigidities" of the labor market in comparison with a "very flexible" situation can have significant impacts on the final results of some studies.

2. Level of professional skills

Another interesting element is the changes that a transition can bring to the level of competence required, and the consequences that these changes can induce.

Indeed, an energy transition can increase investments in new technologies, which can in turn lead to more demand for people in higher skilled jobs. Such a change can have various impacts: higher skilled jobs usually means workers who are better paid, with a higher job quality, but may also lead to a reduced access for women and young people (Cambridge Econometrics, 2011). All these aspects raise desirability issues.

Higher skilled jobs also means higher education time and thus higher inertia for the skills demand to be met.

Recommendations for scenario producers:

The evolution in professional skills and their change rates for each concerned industry in specific country / region should be taken into account.

Scenario producers should provide a narrative around these enabling conditions allowing the transformations to actually be implemented: evolution of skills and its pace should be addressed as well as the underlying need for education and training policies, especially when the proposed scenario includes important variations.

How to train people? What rhythm? How to maintain these skills over time knowing the know-how fades away after years/decades if the skill is not used?

The level of professional skills with regard to job quality and job access should also be qualitatively addressed.

Will the scenario require higher skilled jobs? What are the consequences on job quality? Would some part of the population be more likely to be excluded from these types of employments?

B. Management for job destruction

In the same way job need and skill need are an inseparable duo, job destruction cannot go without human resource management so as to prevent citizens to be left-behind and to avoid long duration unemployment.

Examples in the real world are numerous: when jobs are destroyed, support is needed. Similarly, the expectation of job destruction can generate strong resistance if not well managed. These are again enabling conditions for a job transition.

Thus, putting special effort on workers retraining to enable professional reconversion can be a key element. (IRENA, 2018) underlines that an assessment of the occupational patterns and skill profiles in declining industries is necessary to that extent. They then illustrate what concrete measures professional reconversion may require in terms of job security: "Because reskilling and other adjustments is not always certain to succeed, there is also a need to provide interim support, such as unemployment insurance and other social protection measures."

These are strong desirability issues of a scenario.

Again, management for job destruction can also be linked to the age pyramid of the concerned population. For example, the phase-out of a specific sector is eased when the majority of the workers are old and therefore close to retirement. This has an impact on the 'social cost' of the transition.

Recommendations for scenario producers:

The question of human resource management for job destruction should be addressed.

Scenario producers should provide a narrative around this desirability issue, as significant job destruction could raise strong resistance. They may include considerations on measures for professional reconversion, job security, and age pyramid.

Are some professional reconversions planned? What type of accompanying measures are implemented? In case no accompanying measure is implemented, how are desirability issues handled? How to retrain workers to enable professional reconversion? Are they close to retirement anyway? Which type of support would be needed? Unemployment insurance? Other social protection measures?

C. Stability of employment

Another notion that may be important is the stability of employment. From a total net employment assessment perspective, ten jobs during one year provide the same amount of working hours as one job for ten years. However, this is very different from a job precariousness perspective. Therefore a strong transition on a small timeframe doesn't have the same counterparties as a transition more spread over time.

Recommendations for scenario producers:

Since the different methods of net employment evaluation require to compare an assessed scenario with a reference scenario, all these narrative efforts should also be performed for the reference scenario as well.

The reference scenario may indeed include changes that would require certain elements to be put into perspective.

IV. Bibliography

ADEME. (2012). *L'exercice de prospective de l'ADEME - « Vision 2030-2050 »*.

Breitschopf, B., Nathani, C., & Resch, G. (2012). *Methodological guidelines for estimating the employment impacts of using renewable energies for electricity generation*. 90.

Cambridge Econometrics. (2011). *Studies on Sustainability Issues – Green Jobs; Trade and Labour* (p. 272).

CEDD. (2013). *L'évaluation économique des scénarios énergétiques*.

Criqui, P. (2013). *Quatre trajectoires pour la transition énergétique* (p. 15).

ECF. (2010). *Roadmap 2050 - A Practical Guide to a Posperous, Low-Carbon Europe*.

European Commission. (2011). *Energy Roadmap 2050 - Impact assessment and scenario analysis*.

European Commission. (2018). *A Clean Planet for all - A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy*.

Greenpeace. (2015). *Energy [R]evolution*.

Guivarch, C. (2011). *Évaluer le coût des politiques climatiques: de l'importance des mécanismes de second rang*. Paris-Est.

IRENA. (2018). *Global Energy Transformation: A Roadmap to 2050* (p. 76).

Lappeenranta University of Technology / Energy Watch Group. (2017). *Global energy system based on 100% renewable energy - Power sector*.

NégaWatt. (2011). *Scenario négaWatt 2011*. Consulté à l'adresse https://negawatt.org/IMG/pdf/scenario-negawatt-2011_dossier-de-synthese.pdf

Outil TETE - Transition Ecologique Territoires Emplois. (s. d.). Consulté 4 mars 2019, à l'adresse https://territoires-emplois.org/

Percebois, J. (s. d.). *Rapport Energies 2050*. 392.

Perrier, Q., & Quirion, P. (2017a). How shifting investment towards low-carbon sectors impacts employment: Three determinants under scrutiny. *Energy Economics*, *75*, 464-483. https://doi.org/10.1016/j.eneco.2018.08.023

Perrier, Q., & Quirion, P. (2017b). La transition énergétique est-elle favorable aux branches à fort contenu en emploi ? Une analyse input-output pour la France. *Revue d'économie politique*, *127*(5), 851. https://doi.org/10.3917/redp.275.0851

Quirion, P. (2013). *L'effet net sur l'emploi de la transition énergétique en France : Une analyse input-output du scénario négaWatt*.

Rutovitz, J., Dominish, E., & Downes, J. (2015). *Calculating global energy sector jobs*. Institute for Sustainable Futures.

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The Shift Project

The Shift Project, a non-profit organization, is a French think-tank dedicated to informing and influencing the debate on energy transition in Europe. The Shift Project is supported by European companies that want to make the energy transition their strategic priority & by French public funding.

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Impact assessment
in energy transition scenarios

Technical file #8 – Draft version

Information and recommendations for scenario producers

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Several aspects of the energy transition are handled in these technical files. However, on the energy supply-side only the power system has been studied. The main reason for this choice is that we had to start from somewhere with limited resources, and the power system seemed to be a key system to study in the energy transition context, towards a low-carbon economy, as shown by the growing number of future studies focusing on this system. However, the guidelines we propose could be completed by analyzes on the other energy supply-side systems (the gas system, oil system, heat system and so on).

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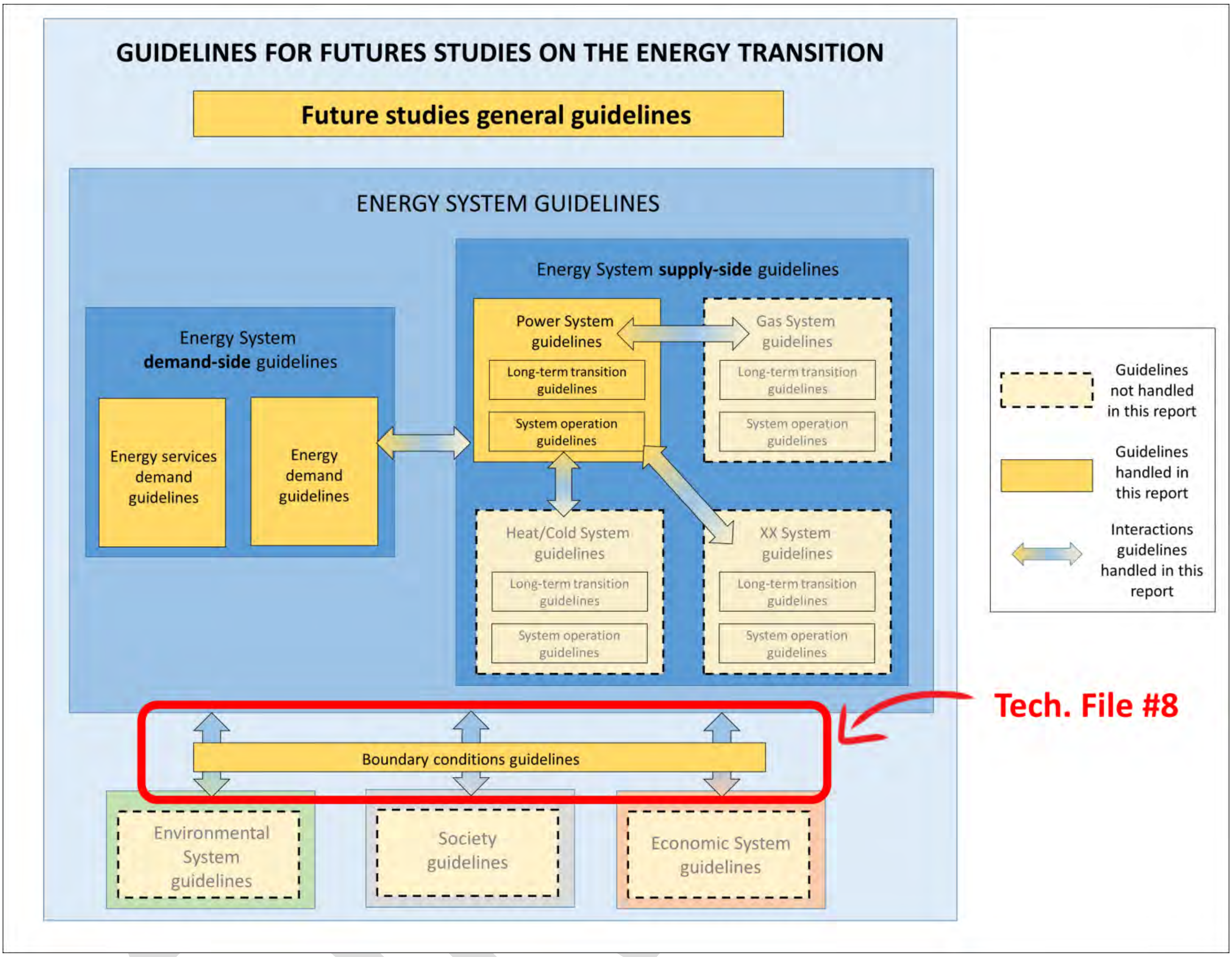

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I. Impact assessment

As described in section about Future studies, impact assessment fundamentally is about telling the story of how systems surrounding the core system[1] (such as the environment, society, or the economy) evolve during the proposed energy transition, due to the activities taking place within a given geographical and/or sectoral perimeter.

Here are a few examples of impact assessments which could be performed by a future study for some or all of its energy transition scenarios:

- providing the yearly CO_2 emissions to the atmosphere due to all the activities taking place within the territory over the scenario timeframe
- providing a qualitative narrative of the evolution of the natural habitats due to the activities linked to the consumption of the people living in a territory, including activities not taking place on the territory (that is, activities to produce imported goods), over the scenario timeframe
- estimating the evolution of the number, and nature, of jobs in the energy sector due to the evolution of the energy-related activities taking place within the territory over the scenario timeframe
- providing a qualitative narrative of the evolution of the lifestyles of different types of households living on the territory over the scenario timeframe

A. Considering different interactions with surrounding systems may lead to different study results, hence the list of considered interactions should be transparent

For each surrounding system (environment, society and economy), a great number of variables can be looked at to provide information about its interactions with the core system transition. The difference in results between a study which considers an interaction (such as the interaction between the energy transition and water use) and another study which does not may be significant. Obtaining a significant result difference would reveal that the considered interaction actually limits the possibilities to achieve some pathways. For example, one may imagine that in a +3°C climate change scenario, water use constraints in Southern Europe may affect the capacity of thermal power plants and of hydropower plants to operate, significantly altering the possible power mixes. Thus, a study which takes into account constraints on water use would get significantly different results than a study which does not take it into account.

Defining the interaction which will be studied may leave room for the choice of specific indicators which inform about this interaction. The choice of specific indicator(s) may itself strongly affect the study's outcomes. For example, CO_2 emissions can be monitored as a yearly flow to the atmosphere or as a stock within the atmosphere, accumulating over the years. For a scenario in which the CO_2 emissions are backcasted[2], a flow approach (e.g. "80% emission reduction by 2050") may drive investments toward lowest abatement costs solutions. It can lead to lock-in effects, and non-optimal emission trajectories from a stock point of view. On the contrary, with a stock approach, the first abatement solutions can be the most expensive ones, the goal being to reduce the cumulated emissions.

Recommendations to scenario producers

The choice of which interactions are considered in the study should be clearly stated, and this list should be substantiated with regards to the driving questions.

For each interaction, chosen indicators should be clearly defined, and these choices should be substantiated with regards to the driving questions.

[1] The core system is the system which undergoes the described transition in the scenario (often, the energy system, or the power system). This system is considered to be interacting with surrounding systems (the economy, society, the environment). See section on Future studies.
[2] For a definition of backcasted components, see section on Future studies: they are those variables whose value is fixed before the modeling as they are deemed desirable by the scenario producer, such as maximum levels of GHG emissions.

For example, are greenhouse gases emitted to the atmosphere considered? If yes, which ones are considered? Is biodiversity considered, and which specific indicators have been selected? What are the reasons of these choices?

B. The inventory (what impacting activities are included in the assessment perimeter) should be transparent

Studies regularly perform impact assessments. Typically, they assess costs, GHG emissions, and sometimes employment patterns. In all those cases, they perform an inventory of the energy system components (or, more precisely, the associated processes and activities, such as building and operation of energy system components) that they consider as impacting.

The first aspect of the inventory is the assessment perimeter which is selected.

The descriptive perimeter has to be differentiated from the assessment perimeter. The assessment perimeter corresponds to the activity perimeter containing the end-consumer's activities (driving one's car, heating one's house) and the activities for the production of goods and services (industrial, or tertiary activities) which are considered for impact assessment (see Figure 1). Two main options exist for assessment perimeter definition:

- Only activities happening within the descriptive perimeter could be considered. This is what most scenarios do. We call this approach the *territory approach*.
- Or, external production activities can be taken into account through imports, and internal production activities be withdrawn through exports. In this case, the geographical assessment perimeter corresponds to a consumption perimeter: *the footprint* of agents consuming in the descriptive perimeter is counted, even if the corresponding impacts originate from outside. We call this approach the *footprint approach*. In this case, another question arises: what agents are part of the assessment perimeter? For example, for individual consumers, are they the nationals of the area (even if they do not live here)? Or, are they people who permanently live in the area (independently of their nationalities)?

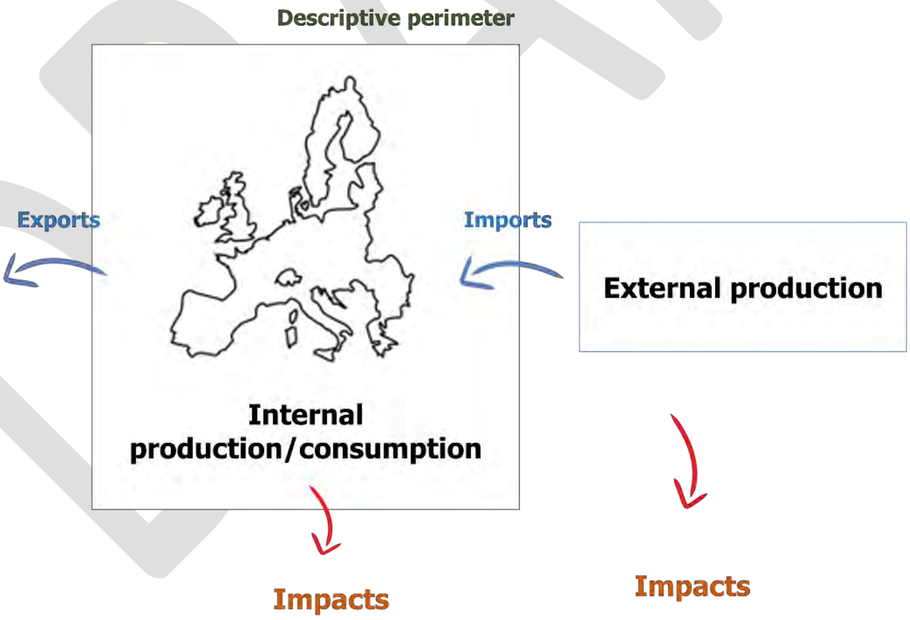

Figure 1: Illustration of the difference between the descriptive perimeter and the assessment perimeter. Here the descriptive perimeter is the European Union (EU) + United Kingdom. Economically speaking, the agents in this perimeter import and export goods and services. Activities taking place within the descriptive perimeter lead to impacts on the surrounding systems. Also, production activities to produce goods and services which are imported within the descriptive perimeter lead to impacts. The footprint approach corresponds to adding to internal production and consumption impacts, the impacts of external production, and withdrawing the impacts of the production of exports.

Mobility and freight are special activities for which some impacts (such as noise, CO_2 emissions, air pollution, accidents…) happen locally while moving and potentially crossing several territories. Such activities may remain inside the descriptive perimeter, such as a truck transporting goods within EU; or, they can entirely happen outside the descriptive perimeter (but still be counted in the assessment perimeter in the footprint case), such as a truck in China transporting intermediary production between two plants for producing a mobile phone which will ultimately be imported and bought in EU. In those two cases, impact allocation is clear: totally within the descriptive perimeter, or totally outside of it.

But some freight/mobility activity may happen both inside and outside the area (such as a truck importing goods from China to EU, or a plane going from Paris to New York City). In this case, a rule has to be arbitrarily defined: for example, half of the impacts might be allocated to internal production and half to the external production (such a practice is adopted in (Association négaWatt, 2014; Association négaWatt, 2017)).

Assessment perimeter depends on the considered core system (power system supply-side, whole power system, whole energy system…), as the activities included in the assessment perimeter are linked to the evolution of the core system. For example, a study about the power system supply-side which has a territory approach would include all the activities related to the power system supply-side over the considered territory (such as what is performed in (ADEME, 2015; ADEME / Artelys, 2018; Agora Energiewende, IDDRI, 2018)). A study about the power system supply-side which takes a footprint approach would include the imports for the capital and operation of the power plants and other components of the power system supply-side[3]. This approach is used in (Hammond, Howard, & Jones, 2013).

Assessment perimeter can be tuned for each considered interaction. For example, a study might choose a footprint approach for CO_2 emissions but a territory approach for economic matter[4].

Once the assessment perimeter is defined, a more precise list of the activities which are included as impacting may be provided. For example, (ADEME / Artelys, 2018) provides a list of all the power system's components which are included in the cost assessment This list actually contains activities that have to be financed (building of power system components, and operating them), rather the power system components themselves. We call this list the *inventory*.

C. The assessment perimeter and inventory must be in line with the driving questions

The choice of assessment perimeter, and inventory, is driven by the driving questions and the storyline. The conclusions that can be derived from an impact assessment depends on the chosen inventory.

For example, let us consider a study which seeks to investigate the effects of reducing overall power demand on costs. The study compares two scenarios: scenario A with a reduced demand compared to scenario B. In scenario A, demand is lower because houses have been insulated, requiring less space heating and water heating. The supply-side system in scenario A is smaller (lower installed capacity, less fuel consumed…) because it fulfills a lower demand level.

Let us compare two different inventories: the first one includes the power system supply-side (from power generating units to the end of the distribution grid) only, whereas the second one further includes the power system's demand-side (all the devices consuming the electricity as well as their technical and organizational environments). With the first inventory, costs are lower for scenario A because demand is lower hence the supply-side is smaller, hence cheaper. With the second inventory though, the assessment is not so clear between scenarios A and B, because in scenario A the transition of the demand side includes the costs of insulating the houses.

In this example, the first inventory enables to answer the question: is a power system fulfilling a lower demand cheaper, or more expensive, than a power system fulfilling a larger demand? This question is of little interest for society (because the cost of houses insulation should be included in the assessment), but it can be interesting for

[3] Such an approach may be called a Life Cycle Analysis (LCA) approach. Indeed, the LCA approach is used to assess the impacts of a product, or service, and it turns out the power system supply-side can be seen as a service (providing electricity). Hence for this perimeter, the footprint approach as described previously, is equivalent to an LCA approach.

[4] For example, the energy transition in EU interacts with the EU economy, but also with the economy of the rest of the world, through imports and exports. It might be too complex to assess the interactions between the EU transition and the economy of other regions of the world. Generally speaking, in this case, the economy of other world regions is fixed by the storyline of the scenario, and only the economic impacts within the EU are assessed.

power systems actors having to size their financing needs in the situation where a law about house insulations have been passed.

The second inventory is necessary to answer the question: are overall costs minimized by insulating houses with regard to the associated impact on the power system? This question investigates the overall effect of the house insulation lever on costs, which is much more useful from a society perspective.

The same line of reasoning can be performed for other impacts. The previous example can be applied to CO_2 emissions, with the following questions:

Inventory 1: does a power system fulfilling a lower demand emit more CO_2, or less CO_2, than a power system fulfilling a larger demand?

Inventory 2: does insulating houses (which is an activity generating CO_2 emissions per say) leads to decrease overall CO_2 emissions with regard to the associated impact on the power system?

These examples illustrate the limits of "supply-side optimization studies" using a supply-side only inventory[5], that is, studies assuming a given level of demand as an input and seeking to compare different power system supply-sides to meet this demand. These studies can bring only partial conclusions about levers acting on demand. Hence they cannot investigate the overall effects of energy efficiency levers, or the overall effects of sobriety levers.

Similarly, the territory approach and the footprint approach do not answer the same questions (Ministère de l'écologie, du développement durable et de l'énergie, 2015):

- The territory approach is centered on production place. It is the oldest approach and is the one used in international agreements for climate impacts. This approach corresponds to the legal responsibility of States (they are responsible for how production is organized on their territories). Hence such an approach informs about States levers.
- The footprint approach is centered on consumption place. It informs about what different consumers (households, organizations, companies…) can do about the considered impacts by changing their consumption patterns. For example, for a power system supply-side study, the consumers are the companies operating power system's components, as they decide what components to buy and install.

Recommendations to scenario producers

A strategy about assessment perimeter(s) definition(s) should be defined and justified with regards to the driving questions. The following aspects may be reported about:

- Territory approach or footprint approach. If the footprint approach is preferred, then the group of individuals which are included in the scope should be precisely defined.
- Specific considerations for measuring the impacts of mobility and freight.
- Differences (if any) in the assessment perimeters for different impacts.
- When assessing the effects of specific levers, considerations on how the assessment perimeter contains the activities impacted by these levers. As a rule, if the driving questions are about investigating the effects of a lever, then the assessment perimeter should include all the activities impacted by that lever.

D. The assessment methodology should be transparent

The interaction assessment can be performed through a model for quantitative assessment, or through a narrative qualitatively linking the obtained energy transition to the considered surrounding system.

The assessment technique depends on each specific impact and indicator. However, the usual methodology consists in listing the different activities happening within the core system during the scenario timeframe (for example, describing all the activities and processes related to the energy sector taking place each year of the scenario) and

[5] (ADEME, 2015; ADEME / Artelys, 2018; Agora Energiewende, IDDRI, 2018) are such studies; (RTE, 2017) has the same approach and acknowledges its limitation.

linking these activities to the considered surrounding system (e.g., GHG emissions in the atmosphere). The link can be straightforward (such as the link between fossil fuel consumption processes and CO_2 emissions, which is a quantitatively linear link) or more complex (such as the link between energy consumption processes and local air pollution).

Recommendations to scenario producers

For each impact indicator, the assessment methodology should be clearly stated and at least qualitatively described. *For example, which model has been used and what are its main mechanisms?*

E. Horizon effects should be tackled to prevent lock-in effects after time horizon and impact assessment biases

As described in section about future studies (II.A.1), the fact that scenarios have an end-date (a horizon) may lead to some results distortions, both in terms of obtained energy transition[6] and in terms of scenario assessment. A few techniques exist to correct, or reduce these horizon effects.

In order to reduce the risks of lock-in effects a first, computational technique is to run the model up to a horizon well beyond the described time horizon. With this technique, the obtained energy transition takes into account the constraints which may happen after the described time horizon, so that the risks of generating lock-in effects after time horizon are reduced. Of course, the hypotheses about what happens after time horizon are key drivers of what will be considered as lock-in effects and what will not. For example, (SFEN, 2018) analyzes scenarios whose time horizon is 2070 and compares them with similar scenarios (E3MLab & IIASA, 2016), ran with the same model (E3Modelling, 2018), whose time horizon is 2050.

A second, qualitative technique, would be to perform the same kind of work through a narrative explaining how the proposed energy transition would not entail adverse consequences for people living during the decades after time horizon.

In order to properly compare the different scenarios across their different impacts even though there is a time horizon, impact assessment can be corrected by incorporating in the scenario timeframe impacts happening after the time horizon. Such a technique is described in section about economic evaluation.

Recommendations to scenario producers

The different techniques to tackle horizon effects should be described. The following aspects should be considered:

- The possibilities of lock-in effects after time horizon generated by each proposed transition scenario
- The impact assessment biases generated by time horizon

[6] Taking into account the so-called lock-in effects may change the scenario results.

Bibliography

ADEME. (2015). *Un mix électrique 100% renouvelable ? Analyses et optimisations*.

ADEME / Artelys. (2018). *Trajectoires d'évolution du mix électrique 2020-2060 - Synthèse*.

Agora Energiewende, IDDRI. (2018). *L'Energiewende et la transition énergétique à l'horizon 2030*.

Association négaWatt. (2014). *Scénario négaWatt 2011-2050 - Hypothèses et méthode*.

Association négaWatt. (2017). *Scénario négaWatt 2017-2050 | Dossier de synthèse* (p. 48).

E3MLab & IIASA. (2016). *Technical report on Member State results of the EUCO policy scenarios* (p. 381).

E3Modelling. (2018). *PRIMES MODEL VERSION 2018 - Detailed model description* (p. 221).

Hammond, G. P., Howard, H. R., & Jones, C. I. (2013). The energy and environmental implications of UK more electric transition pathways: A whole systems perspective. *Energy Policy*, *52*, 103-116. https://doi.org/10.1016/j.enpol.2012.08.071

Ministère de l'écologie, du développement durable et de l'énergie. (2015). *Stratégie nationale bas-carbone* (p. 208).

RTE. (2017). *Bilan prévisionnel de l'équilibre offre-demande d'électricité en France*.

SFEN. (2018). *Le nucléaire français dans le système énergétique européen*.

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Nicolas Raillard joined *The Shift Project* as a Project Engineer. A graduate from ISAE – Supaéro (France) and from the Georgia Institute of Technology (USA), he worked as a complex system strategy engineer in aerospace for 4 years. Having passed an Advanced Master in "Environment International Management" at the Mines ParisTech school (France) and Tsinghua University (China), he now applies his skills and qualifications to the low-carbon transition.

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Economic evaluation of energy transition scenarios

Technical file #11 – Draft version

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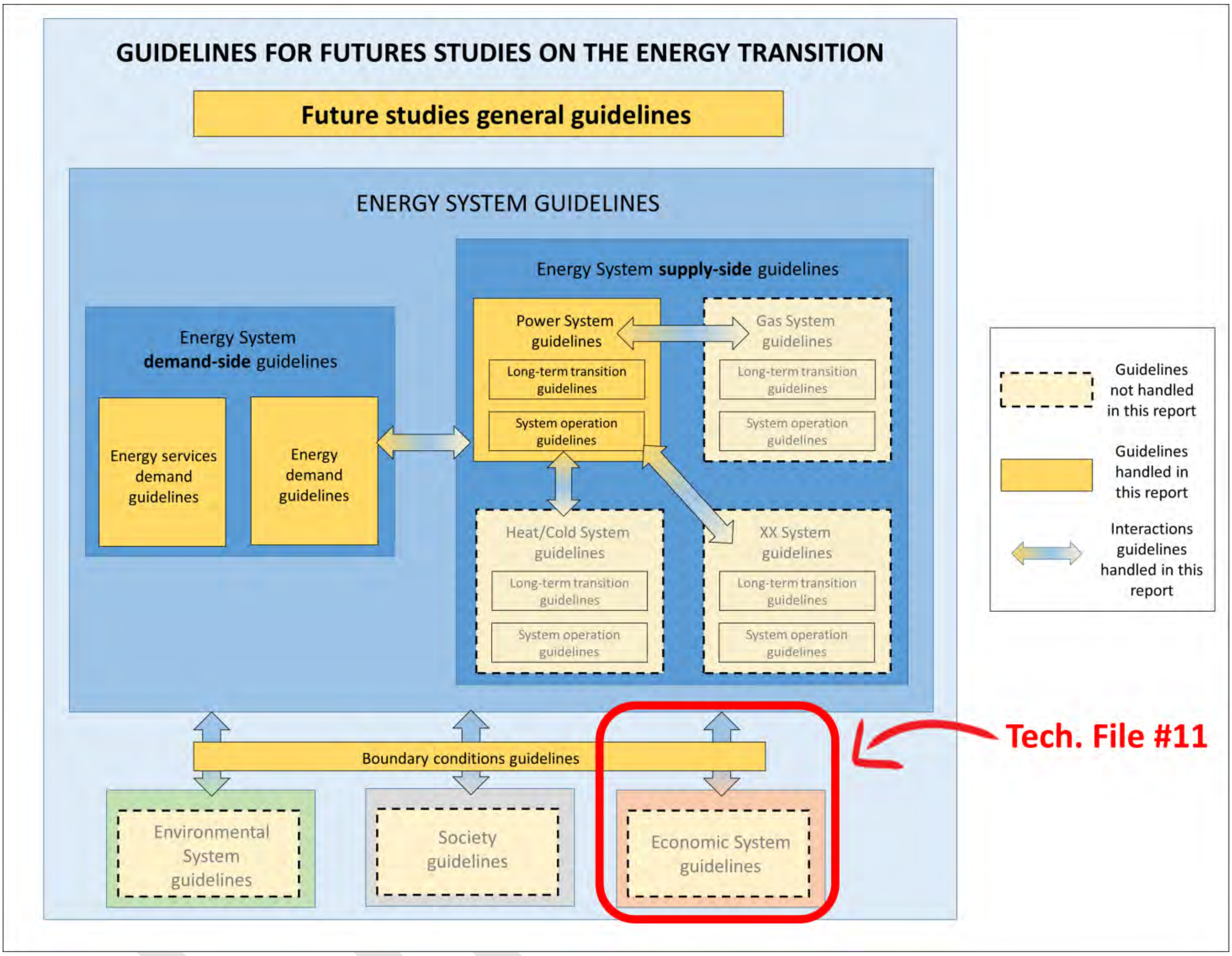

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I. Overview

We provide here a methodological framework to carry out economic evaluations of a technical nature.

It is based on a system approach which consists in assessing and comparing systems rather than technologies and to focus on this system perspective rather than on specific actors' point of view. We argue this approach is better adapted to inform public decision and thus should be preferred in economic evaluation.

This section addresses scenarios economic evaluations.

Economic evaluation questions are often subject to high expectations since it remains an important aspect of fact-based political discussions. However studies presents their own insights and results using very disparate methods, with different scopes and indicators. As a result, it is very difficult to use a set of studies to draw new conclusions, to make knowledge emerge, and thus to better inform the debate on energy transition.

We want here to address this issue by proposing this methodological framework. As explained in the general introduction (see corresponding part), the goal of the Power Systems 2050 project is twofold: sharing best practices so as to give scenario producers the opportunity to benefit from them and proposing tools allowing them to adopt a common "language" so as to foster a common effort. The framework proposed here is part of this process. Our goal is that scenario producers appropriate this method. This would allow scenario producers both to have a flexible and clear method for economic evaluation of their studies, and to participate in a common effort by agreeing to respect a shared standard for greater transparency.

This methodological framework is based on a system approach and is structured around three elements: the possible adopted points of view, a power system inventory, and the choice of adapted cost indicators. It is designed to carry out economic evaluations of a *technical* nature (as opposed to evaluations of a *macroeconomic* nature). System approach has been described in (Agora Energiewende, 2015) and the framework structure has been inspired by (RTE, 2017). What is presented here is a combination and exploration of a resulting structure that we believe can constitute a clear and usable tool for scenario producers to foster enlighten discussions. We tested it on several studies such as (Fraunhofer ISE, 2015) or (ECF, 2010) and it seemed to apply quite easily.

NB: The framework has been described for power system only. The same approach could probably be generalized for energy system as a whole thanks to some specific adjustments (as adding all the conversion systems enabling to convert energy carriers into another form for example). The philosophy would remain the same.

System approach consists in assessing costs required to *make the system work*, and only those costs. Total system costs is a reflection of the real overall effort, of the amount of time spent and resources mobilized to build and operate the assessed system. Therefore, system perspective contrasts with both focuses on technologies and on specific actors' point of view. We do support the opinion shared by Agora Energiewende and RTE among others: system perspective is better adapted when trying to inform public decision and should therefore be preferred in economic evaluations.

Here is an overview of the content of this technical file.

A first part introduces the distinction between costs of a technical and macroeconomic nature, as well as general considerations on the use of cost indicators. Then, three types of study are defined. Several elements depend indeed on the type of each study, such as the type of economic evaluation that should be used (technical or macroeconomic), or the inventory perimeter and the choice of cost indicators.

The core elements of the methodological framework are then described as followed:

- Possible points of view are the perspectives from which the costs are being looked at. It can be either system as a whole or one specific actor such as the State, electricity system actors, or final electricity consumers. We explore this categorization: not being clear about the chosen point of view in an analysis leads to classic misunderstandings and only the costs assessed from the same perspective can be compared. It should thus be clearly stated before any comparison. We also highlight the fact that the often mentioned "cost to society" does actually not relate to any specific perimeter and thus that "system perspective" should be preferred over "society perspective" as it is much clearer. In addition, system perspective better enlighten public decision but specific actors' perspective can also be useful to bring complementary insights.

- Power system inventory gives an overview of all the power system components requiring expenditures to build and operate the system during the scenario timeframe. It details all the subsystems related to electricity production, network (transmission, distribution and interconnection), consumption (including energy demand management), storage, power services, operationalization, vector shifts and adaptation and repairs due to climate change. The assessed elements within this inventory differ among scenarios and should thus be clearly stated so as to be able to properly compare the costs.

- Choices of adapted costs indicators are then explored, both for system perspective and specific actors' perspective analysis. To compare and evaluate costs from a system perspective, a table of system technical cost indicators is presented, a set of recommendations to carry out a proper comparison between scenarios is detailed, and three specific system technical indicators and their respective uses are defined and explored: expenses shape to visualize the time evolution of financial effort of one scenario, differential costs to properly compare two scenarios and absolute costs to understand the cost evolution with today's situation. To assess costs from a specific actor's perspective, we provide a discussion about price and cost of energy for final consumers. Finally, the five cost items required to calculate system technical cost indicators are presented: the often used CAPEX and OPEX, but also electricity trade balance, future costs and past costs. This classification has already been proposed by (RTE, 2017) and is developed here. Methods to calculate each cost item are described with some complementary tips and information. Cost elements that has to be added to assess costs from specific actors' point of view (i.e., economic transfers) are discussed as well.

II. How are costs usually handled in future studies?

A. Two types of costs to assess and compare scenarios: technical, and macroeconomic

The notion of cost is not straightforward, even though cost is extensively used to assess and compare different scenarios, or even to drive energy transition in scenarios (such as scenarios driven by a cost-minimizing benevolent planner).

The cost of an action can be defined as the difference between the cost of a Business as Usual (BAU) scenario and a scenario in which the action is performed. In this definition, who bears the cost is not defined. Intuitively, a cost is incurred by some economic agent (a household, a company, the State…). However, in our context, we seek to characterize the cost to *make the system work*, as opposed to a cost for such or such agent.

Concretely, the cost of a transition (defined as the cost of all the actions involved in the transition) is an indicator which may be useful to inform some decisions regarding the energy transition. The information this indicator provides depends on how it is computed.

Practically for future studies, the cost of an action or of a set of actions is usually computed in two ways, each way transmitting a different meaning, and each of them being associated to a different types of modeling (Guivarch, 2011).

The first type of cost is called *technical cost*. Technical cost is the difference between two scenarios (one of them considered as the Business as Usual) of the investment cost, or of the total operating cost (investment and operation cost) incurred by the technical systems (power plants, vehicles, house insulation, cement production technologies and so on), discounted over the scenario timeframe. This indicator does not take into account the interactions between the described technical systems and the rest of the economy: it is a partial economy indicator, as its computation includes only some sectors of the economy.

The second type of cost is called *macroeconomic cost*. This indicator takes into account all the interactions between the sectors considered for the transition and the rest of the economy. In a word, this indicator takes into account the propagation of technical costs into the whole economy, through wages of the technical sectors being spent in the rest of the economy, or through the effects of the evolving offer on consumers, who reorganize the way they spend their money (for example in case of electricity price evolution).

This indicator accounts for a number of macroeconomic effects such as eviction effects, or rebound effects. Eviction effects happen when an actor invests in domains she would not have invested in without the transition, at the expense of some other domains. Rebound effects happen for an actor when she saves money due to some efficiency, or sobriety measures, leading her to spend her savings in other domains she would not have spent her money in otherwise.

This indicator can be computed as a GDP difference between two scenarios. It is a general economy indicator, as its computation includes the whole economy.

Computing technical costs requires technology-rich models (see section on consumption). Most often those models either do not consider economic variables, or consider only the economy of the energy sector. As a result, those models do not compute macroeconomic costs.

On the other hand, computing macroeconomic costs requires a macroeconomic model. Macroeconomic models are not technology-rich enough (their level of technological aggregation is too high) hence they cannot properly compute technical costs.

B. How should those indicators be used? Are they sufficient to inform energy transitions?

Technical costs inform about the overall expenses involved by changes on the energy system, and incurred by all the actors involved in the financing of this sector. Concretely, a lower technical cost means that the changes on the considered energy system have required less human work or capital[1], and/or less costly human work or capital. In a way, technical cost represents the amount of human effort to perform the energy system transition. It is an indicator of cumulated effort along the transition. In a sense, a transition involving less technical costs leaves more available workforce and capital for other economic activities (assuming demography is unchanged between the two compared scenarios).

Macroeconomic cost as a GPD difference at a given time during the transition represents the effects of the transition actions on the overall size of the economy, as measured by GDP. GDP per inhabitant represents the average consumption volume of each inhabitant, without taking into account the quality of this consumption.

Note that those indicators do not include any consideration for physical limits of the planet. They do not include neither any consideration on the evolution of lifestyles and cultures. Hence those indicators have to be completed by other indicators and narratives in order to provide a more complete view of the proposed transition.

C. Other economic variables can also be assessed through technical, or macroeconomic indicators

Generally speaking, economic variables such as purchasing power, employment or balance of trade can be assessed by a technical approach or by a macroeconomic approach.

The technical approach consists in assessing the implications within the energy system perimeter of the actions to change the energy system.

A technical assessment of job employment during the transition and as compared to a BAU scenario, would be to assess the evolution of jobs directly involved in the energy transition (on the supply-side and demand-side of the energy system). For assessing balance of trade, the trade with other regions of goods and services directly involved in the energy transition would be taken into account, such as the trade for cars, for energy, for power plants and so on. Similarly, a technical assessment of purchasing power during the transition would be to assess the direct effects on households' expenses of the energy transition, such as energy savings from house insulation and electric cars, more expensive electricity and so on.

This approach does not provide the full picture though, because macroeconomic effects are not taken into account (see Figure 1). For example, employment rate could increase during the transition, which could raise wages and hence affect the balance of trade. Such an effect would not be taken into account with the technical approach. Technical purchasing power does not take into account the fact that people will be employed for house insulation, raising the employment rate, hence raising GDP and raising the average purchasing power.

[1] The price of a good or service (without tax) is the sum of the wages and rents that have been transferred to workers who participated in producing, transporting, installing, selling etc this good or service, and owners of production tools or land involved in that good or service (Jancovici & Grandjean, 2009).

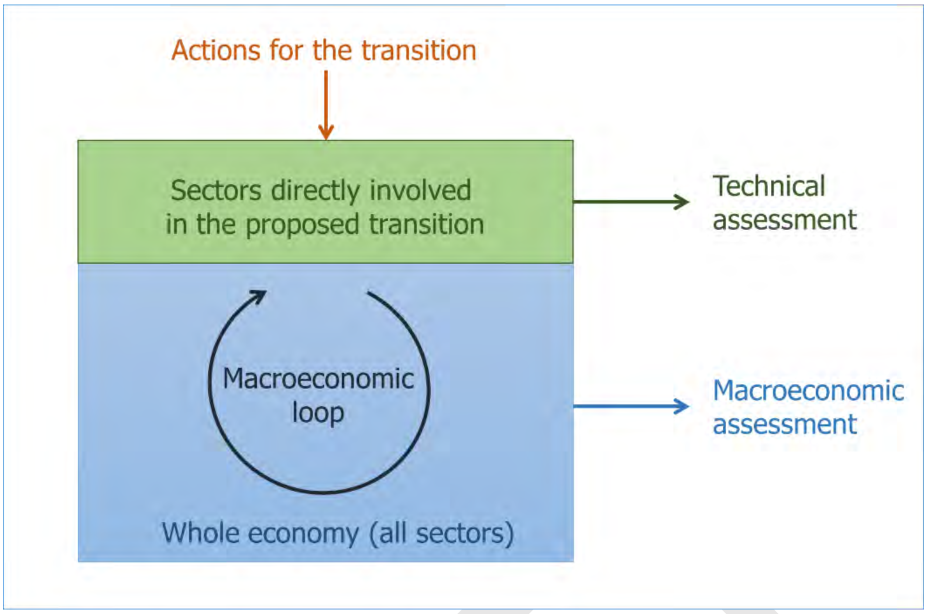


Figure 1: Illustration of the economic sectors which are included in technical assessments and in macroeconomic assessments.

These sectors evolve, as compared to a BAU scenario, under some actions for the transition. These actions can be investments, regulations and bans, taxes and subsidies, or actions undertaken by the modeled benevolent planner.

These macroeconomic loops are simulated in the macroeconomic approach. However, this approach is based on complex models which can hardly be understood by people who do not work on a daily basis with them, which are based on different macroeconomic theories with no clear account of why such theory should be used for such case and which are too aggregated to be concrete enough in explaining the results to stakeholders.

The future studies we reviewed compute no cost indicator, or they compute technical costs. We propose in the following section a framework aiming at fostering transparency when it comes to technical cost computation.

III. Proposed framework: an explicit methodology for technical economic evaluations

This framework explores a methodology enabling scenario producer to carry out an economic evaluation of a *technical* nature. Therefore, the further presented power system inventory and technical system indicators table are only viable for technical evaluation (consideration about possible points of view do apply both for technical and macroeconomic evaluation). As previously explained, a technical evaluation focuses on the energy system whereas a macroeconomic evaluation focuses on the entire economy. Therefore, in the case of a macroeconomic assessment, the use of a model is necessary, the inventory becomes the whole economy, and the indicators used are not technical ones but rather macroeconomic ones such as GDP gaps. Next paragraph introduces a distinction between three types of studies that drives this kind of choices.

Then, as described in the overview, the three main parts of the methodological framework are presented: possible points of view, power system inventory, and cost indicators (see the overview paragraph for a summarized description of these three parts).

A. Three categories of study: some of the main economic evaluation choices depend on the levers activated in the study

We define here three main categories of studies, which determine certain choices related to economic evaluation, particularly concerning the inventory and the main indicators used.

These three categories are distinguished according to the levers activated to ensure the balance between supply and demand:

- The first category uses levers on the supply-side only.

- The second category activates levers both on the supply and demand-sides, without the *demand sobriety* lever (see Demand section).

- The third category activates levers both on the supply and demand-sides, including the demand sobriety lever.

1. Supply-side studies

These are those that activate levers on the supply-side only, which means only options that can affect the supply system are available in the considered scenarios.

Some of these studies set a single level of input demand, while others test several different levels of demand, but in any case no action that could affect the demand system is possible to ensure the supply-demand balance.

The majority of future studies fall into this category. For this type of study, both a technical and a macroeconomic evaluation are viable. The framework presented here can therefore be used. In this case, the PS inventory can be used, with the demand-side remaining neglected. System technical cost indicators (see corresponding paragraph) are suitable for evaluating the modelled system, with the possibility of using indicators focused on the supply system such as s-LCOE.

2. Supply & demand-sides studies without demand sobriety

These are the ones that activate levers on the supply-side but also on the demand-side, without however giving the possibility to introduce demand sobriety. Thus, the construction of pathways includes options that can affect the demand system, such as different energy efficiency measures. It makes it possible to integrate a trade-off between reducing demand and increasing supply in order to achieve a supply-demand balance.

This is the case for some studies using the PRIMES model, or for (Fraunhofer ISE, 2015) for example. The importance of taking into account the consumption side, and in particular the reduction of energy consumption, is increasingly recognized (CEDD, 2013).

For supply & demand-sides studies without demand sobriety, as for supply-side studies, a technical evaluation as well as a macroeconomic evaluation are viable. Thus, the framework presented here can also be used for this type of study. The PS inventory is adapted, both with its supply and demand-sides, as well as system technical cost indicators. For such studies, indicators focused on the supply system only are of little use. On the contrary, indicators that integrate both supply-side and demand-side costs of the system (allowing to simulate supply-demand tradeoffs) are more appropriate.

3. Supply & demand-sides studies including demand sobriety

These are the ones that activate levers on the supply and demand-sides, including the demand sobriety lever. We call *demand sobriety* a reduction of *human demand* (see Demand section). This type of lever is used in studies such as those conducted by négaWatt Association.

We argue an economic evaluation of a technical nature is not appropriate for this type of study because it does not allow certain important phenomena to be taken into consideration. The framework presented here cannot therefore be used without an additional consistent macroeconomic analysis, with an inventory including the entire economy and the use of system indicator of a macroeconomic nature such as GDP gap between scenarios. Otherwise, the counterparties related to the demand sobriety lever would not appear correctly.

Indeed, we believe that there is a strong causal link between energy consumption and GDP. This thesis, which can seem quite obvious to intuition, is discussed and supported by a whole part of the literature (see studies such as (Belke, Dobnik, & Dreger, 2011) or (Giraud & Kahraman, 2014), which also present literature reviews on the subject). This means that a decrease in energy consumption via a decrease in human demand (i.e. a decrease of in 'overall' activity, see Demand section) logically leads to a decrease in economic activity and therefore ultimately to a decrease in GDP, all other things being equal.

And while energy efficiency measures enable to decrease energy supply without reducing the human demand, demand sobriety measures reduce human demand. Therefore we argue this framework enables to compare scenarios with the same human demand only.

NB: Demand sobriety can at the same time lead to an increase in free time, happiness, etc. We do not believe that the demand sobriety lever should be neglected, quite the contrary. It is indeed a demand lever very rarely used in scenario studies which makes it possible to introduce non-technological measures. Moreover, given the urgency of the situation about climate issues and in order to monitor emission reduction trajectories in line with Paris Agreement, it may seem relatively logical to activate a variety of possible levers. Introducing demand sobriety lever in addition to other usual levers can therefore be a very appropriate approach.

B. Possible points of view: being clear about the chosen point of view avoids misunderstandings and system perspective better informs public decision

1. Several points of view can be adopted to assess power system cost

Every cost can be assessed from different points of view. We will distinguish in the present framework two main types of points of view: system perspective and specific actors' perspectives.

On the one hand, system perspective relates to costs *to make the system work*, and only those costs. It seeks to assess the cost as a PS aggregate actor, considering only the necessary expenses for the PS (both on supply-side and demand-side) to operate as opposed to any other monetary flow between specific actors within the system (such as taxes, power expenses, etc.) These costs are ultimately paid by society as a whole (i.e., by final consumers, tax payers, etc.)

On the other hand, there are three main different points of view of specific actors related to power system:

- The State, when it deals with PS affairs.

- Power system supply-side actors, such as power producers, transmission system operators, electricity suppliers, etc.

- Power system demand-side actors, usually called final electricity consumers. They can be subdivided into households and industry.

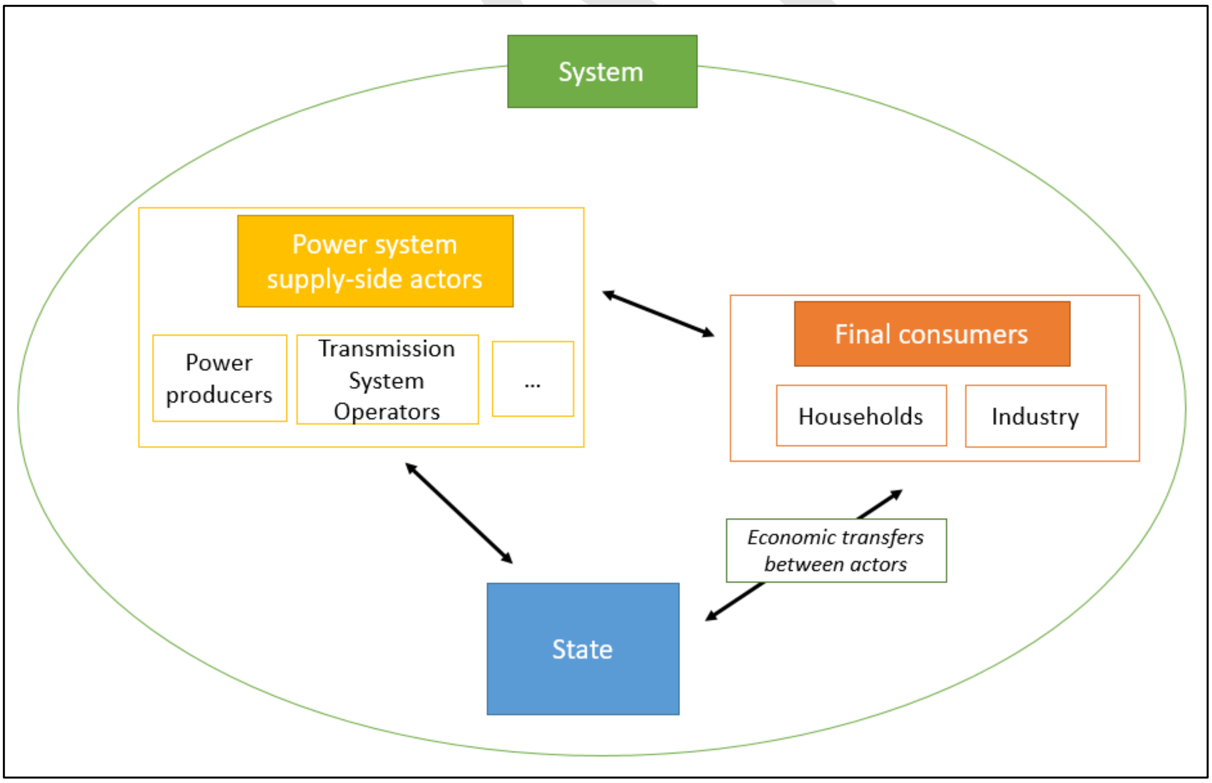


Figure 2: The diversity of points of view to evaluate the costs

The choice of a point of view is very important in an analysis. Depending on the chosen perspective, the same element can be been seen as having negative or positive impact. Here is an illustration from (Agora Energiewende, 2015):

"As in any other market, entrance of a new producer tends to have a negative impact on the return on investment of existing producers. From the perspective of consumers, who do not have to pay for capital invested into existing power plants, the new entrant may appear as a positive effect if it induces lower power prices on the market. From the perspective of the owner of an existing power plant, reduced utilization will be a negative effect, leading to lost revenues and reducing the plant's value. From the perspective of an environmental agency, a change in power plant structure that reduces, for example, the utilization of lignite power plant and their emissions represents a benefit, not a cost."

2. Being unclear about the chosen point of view is a classic reason for misunderstandings

According to (RTE, 2017), the diversity of possible points of view is a classic reason for misunderstandings.

Firstly, one study can use several points of view. Indeed, it can be interesting to analyze the results of a study from different angles. However, not being precise about the choice of perspective make these results unclear.

> Recommendations for scenario producers
>
> For each result analysis, the point of view used should be clarified at the very beginning. It enables to consistently use several perspectives in the same study.

(Fraunhofer ISE, 2015), for example, is presenting results from a system perspective first, and then makes some assumptions on taxes to evaluate the costs from households perspective in a second time, with a clear distinction. Another example can be found in (ADEME / Artelys, 2018): one paragraph describes the consequences of an evolution of market prices first on revenues evolution for nuclear power producers, and then on savings for the State. Points of view are well clarified. It enables it easily understand the objective of each analysis.

Secondly, many analyzes fall into the trap of trying to compare several studies that are using different points of view. However, these are not comparable. Some studies themselves can fall into this trap too when presenting their results. It can of course lead to incorrect conclusions.

> Recommendations for scenario producers
>
> When presenting results, only those using the same point of view should be compared.

3. Society point of view is often mentioned but never defined: system perspective should be preferred

Many future studies refer at some points to 'costs to society'. Some of them sometimes claim to evaluate these costs and thus providing indicators informing society as a whole. However, what is meant by this term is never defined: 'cost to society' don't relate to any specific perimeter.

The underlying idea behind the 'costs to society' concept would be that these are the 'global' or 'ultimate' costs when 'everything' has been included. It would be representing the 'real overall effort', costs that it would be 'right' to minimize. It even seem to also refer to 'non-monetary' costs, as if the concept would go beyond a sum of expenses and revenues. If we try to translate this into a definition, the costs of "something" for society would be the sum of all 'costs' (in the broadest sense) that all the stakeholders related to this thing would have to bear. As we can see, this is a very vague definition.

In addition, what type of evaluation would enable to measure such costs? An economic evaluation of a technical nature (i.e., that does not take into account macroeconomic feedback loops) would probably not allow to cover this whole scope. And does an assessment of a macroeconomic nature really enable to draw a clear conclusion about a 'social' optimum?

Furthermore another unclear element related to 'costs to society' perimeter is the externalities: should costs related to impacts on other stakeholders in the long-term be included? The concept of 'costs to society' is used in many other fields than future studies, and externalities can be included or not (De Clerck et al., 2018). In the case of illnesses for example, 'costs to society' may include the direct costs paid by patients and hospitals, the absenteeism costs paid by companies, and it is not clear whether costs related to mortality (which are not real costs but the internalization of an externality, see Externality paragraph) are part of the definition (Wang et al., 2016).

In the end, it seems that **the use of 'costs to society' concept for economic evaluation of a given s**cenario is not a relevant approach since it has no precise meaning.

However, the concept of 'costs to society' is sometimes used to designate the overall costs within the assessed system as opposed to costs from a specific actor's point of view, with the idea that this perspective better informs public decision. It is true that 'total' cost of a system better enlighten the debate, but we prefer to use the concept of system perspective for this purpose: once the assessed system is clearly defined, the 'total' costs are the costs *from a system perspective*. The only thing that could consistently be said about society in this context is that 'society as a whole' (i.e. final consumers, tax payers, etc.) will have to pay for these system costs. But system costs don't aim at covering all the unclear perimeter of costs that 'society' will have to bear.

4. System perspective better enlightens public decision

As previously defined, system perspective relates to costs *to make the system work*. We argue that system perspective is a better way to compare policy options. This is an idea that has already been put forward many times, as in (RTE, 2017), (Agora Energiewende, 2015) or (OECD, 2012).

For example, after discussing about the limitations of an indicator such as the i-LCOE (see LCOE section), the study (OECD, 2012) states: "[There is] an increasing awareness of a need for a system approach to cost accounting also at the level of decision-and policy-makers." (Agora Energiewende, 2015) explores this idea under the term 'Total system cost approach'. The underlying idea of this approach is that public decision is better informed when studies are focused on system as a whole rather than on specific technologies, and from a system point of view rather than a specific actor's point of view.

> Recommendations for scenario producers
>
> As supported by Agora Energiewende and RTE among others: system perspective better informs public decision and should thus be preferred in scenario economic evaluations.

Therefore, all the further presented methodological framework is designed from a system perspective. We tested the framework on several studies and it applied properly. Thus, we believe it can answer the methodological challenges to the use of total system costs approach.

NB: Assessing costs from a system perspective means that the focus is on the system as a whole. However, it is possible to specify how these system costs are analyzed. It is thus possible to define subcategories of the system perspective. For example, we use the concept of *benevolent planner perspective* to refer to a total system cost that has been calculated with a social discount rate. This is one of the possible specific ways to look at system costs

a. Total system costs is a reflection of the real overall effort and should therefore not include economic transfers between actors

Total system costs is a reflection of the real overall effort, of the amount of time spent and resources mobilized to build and operate the assessed system. It could be approximated with the sum of all the wages, rents and annuities involved[2].

Therefore system costs do not include economic transfers between actors such as taxes and subsidies (see Economic transfers paragraph for more details). These are indeed expenses and revenues that do not reflect an effort or a number of hours of work, but rather a money transfer between actors. They should not be taken into account in system costs. Note that if the two "sides" of an economic transfer are taken into account (i.e., both the expenditure of an actor and the corresponding revenue of the other actor), it get canceled in the sum. To avoid counting errors, not counting them remains the simplest option.

b. System perspective as opposed to specific actors' perspective

System costs effectively makes it possible to understand which option is optimal for the system under consideration rather than for particular actors. The possible points of view do not offer the same understandings. When it comes to enlighten public decision, a specific actor's perspective is incomplete. More precisely, results obtained with a specific actor's perspective does not bring enough information to inform the debate for a proper public decision. Typically, analyses about the bankability for a type of technology in the mix cannot inform the overall performance of the global mix. As explained in (RTE, 2017), the same measure can have both a positive impact on some actors and a negative impact on others. Therefore the best way to evaluate this measure is by choosing to focus on the system as a whole.

Yet, specific actors' perspective can of course provide further useful insights. Some specific questions cannot be answered a 'pure' system approach like issues concerning only some actors and interactions between them. Specific actors' perspective can for example enlighten issues such as bankability for power system supply-side actors or purchasing power for final consumers. However such evaluation requires greater attention, such as the integration of economic transfers between actors. This aspect is developed in the Cost indicator part.

c. System perspective as opposed to a focus on specific technologies

Using a system approach is also much more appropriate for determining what is optimal at the system level rather than focusing on specific technologies. This idea is already developed in the LCOE section. Indeed, to put it shortly, even if it was possible to determine what the «cheapest technology of all» is, the optimal mix would probably not be 100% composed of this technology, especially because each installation provides a different set of "services" to the system (see Power system Operation section).

Here is a summary of Agora Energiewende's stance about this issue:

> Summarized description of the total system costs approach as opposed to a technology focus as described in (Agora Energiewende, 2015)
>
> The questions for policymakers in charge of long-term power sector development is **"What are the implications of choosing path A or path B?"** (rather than "How can different power generation technologies be compared?" for example)
>
> For political decision-making, the comparison of total system costs in different scenarios can be a more appropriate tool. A comparison of the cost and benefits of certain components of the system, such as renewables or nuclear power plants, may be additionally performed, but is not required.
>
> The key insight informing this approach is that society as a whole must bear the costs of the power system, regardless of redistributive effects and how costs are defined.
>
> Total system costs approach has been used - in different variations - in a large number of studies including ECF Roadmap 2050 (2010), EU COM Roadmap (2011), McKinsey & Company (2010), Consentec (2013).

[2] Thus this cost can change according to the country because the same wages differ from one country to another.

C. Power system inventory: what is in and what is out of the system needs to be defined

As previously explained, the presented framework is designed for economic evaluation of a technical nature. Thus, the following section about system inventory is not adapted for macroeconomic evaluation (in such type of economic evaluation, the inventory is the economy as a whole).

1. The power system inventory should be explicit to enable inter-study comparison in cost assessment

Power system is composed of several subsystems. Taking all these subsystems into account is a complex task. This is why most studies only focus on one or several subsystems but not all of them: production part only, production and transport, etc.

From one study to another, the choices are different. For example (ECF, 2010) takes into account generation, transmission, distribution, interconnections, and part of consumption costs through energy efficiency ; while (Lappeenranta University of Technology / Energy Watch Group, 2017) assesses generation, transmission and storage. One can easily understand that the economic evaluations of these two studies cannot be directly compared.

However, some studies are not explicit about what they consider. In these cases, what is in and what is out of the assessed system cannot be clearly identified by study users. This makes the use of a diverse set of studies complicated.

Recommendations for scenario producers

When performing an economic evaluation of several scenarios, the evaluation perimeter should be clearly stated and described.

What subsystems are considered in the cost evaluation?

2. When comparing two scenarios their inventories should be both similar and sufficient

Once an explicit inventory has been described, scenario comparison becomes easier. Trying to apply such framework to existing scenarios sometimes reveal incorrect comparisons. It can happen for scenarios from different studies or within the same study:

- Economic evaluations of scenarios based on different inventory are sometimes compared and analyzed as results of studies.

- Sometimes, scenarios using the same inventory are compared, but the **inventories are not "sufficient": they** do not cover all the changing elements between the two scenarios. An example of insufficient inventory would be the comparison of the overall costs of two scenarios based on a similar inventory focused on supply-side only while there are significant changes on demand-side in one scenario.

In both cases (nonsimilar and insufficient inventories) it can lead to incorrect conclusions.

Recommendations for scenario producers

Before presenting a cost comparison between several scenarios in a result section, scenario producers should make sure all the compared scenarios are based on both similar and sufficient inventories: inventories should be the same, and should cover all the subsystems evolving differently from a scenario to another.

Otherwise it should be explicitly stated, so that the comparison can be analyzed with special care.

3. Power system inventory components

The following inventory is designed to answer the issues presented in the preceding paragraph. By doing so, it also allows to use more wisely the cost indicators later explored.

This "Power system inventory" focuses on power system from a system perspective: it describes the set of power system components required to make the system work. The same logic could be applied to the overall energy system and would require to add some elements such as inter-carrier conversion systems.

Here is a sketch of the power system inventory:

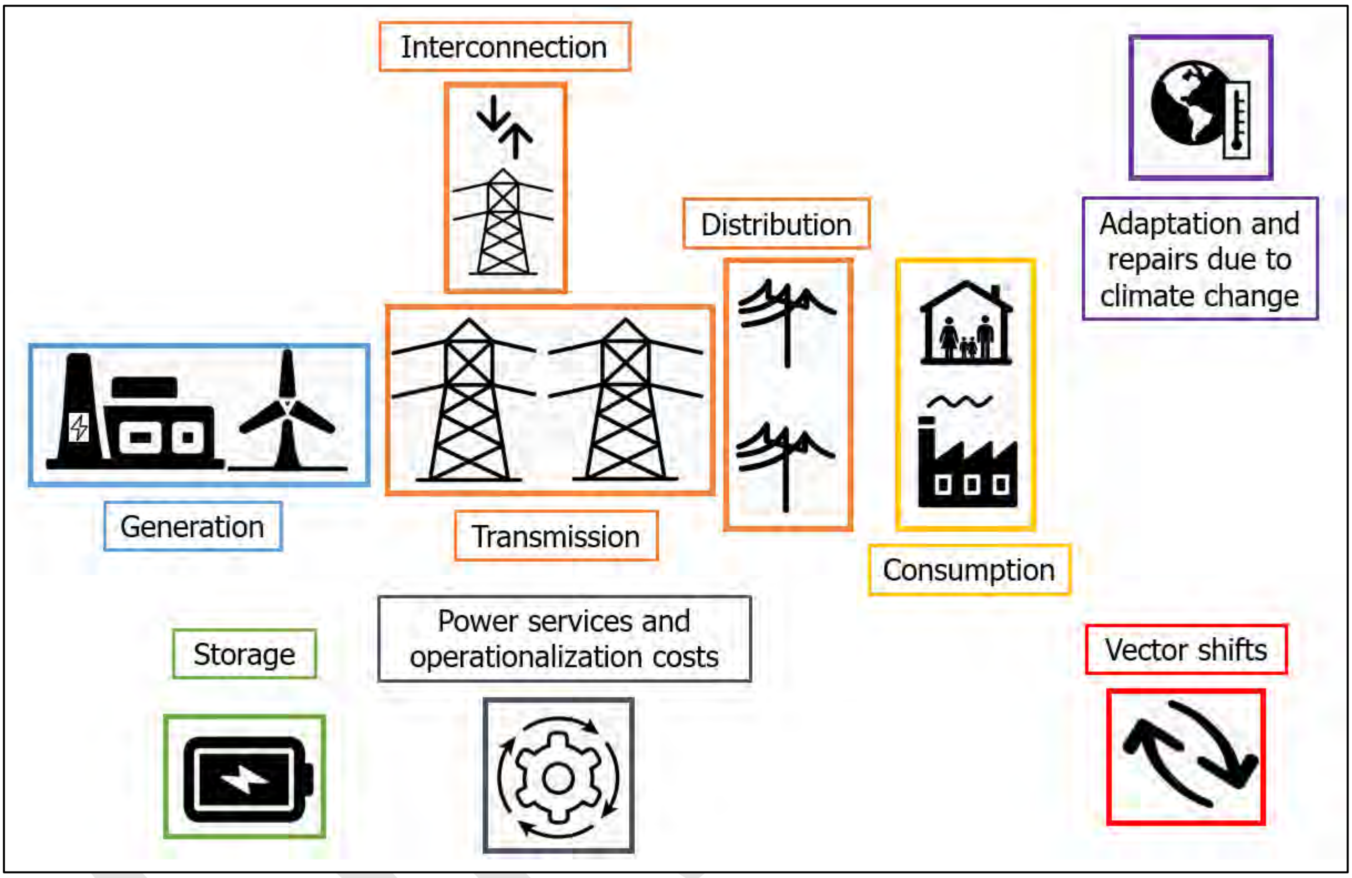


Figure 3: The power system inventory is composed of all the elements required to build and operate a power system.

All these components are described below.

- Production costs

It covers all costs required to effectively produce electricity:

- Investments related to the development and the end-of-life of new generation capacities and the extension and end-of-life of already-existing ones, including financing costs (i.e. capital costs).

- Fixed and variable operation and maintenance costs needed to run the infrastructures such as maintenance costs, fuels costs or waste and pollution management like fumes treatment for example.

- Network costs

It covers all the costs needed to transport electricity from its production place to its consumption place. It also includes costs needed to ensure a proper security of supply (frequency, voltage control) and quality of supply.

Electricity transport and security of supply is managed at grid level through three components in real time interaction with production and consumption sectors: transmission network, distribution network and interconnections. Each part requires significant investments and operation and maintenance costs, especially for the creation of new lines and the renewal of already-existing ones so as to increase the capacity, for the connection of new power plants to the grid, and/or for demand-supply balance. This last element requires control equipment and specific mechanisms (see System Operation section) which costs are borne by transport and distribution sectors but also implicitly by all other sectors[3].

Furthermore, network development is often subject to strong social and environmental acceptability constraints. Therein lines can possibly be buried instead of being aerial at an approximately 5 to 8 times higher cost (Brown et al., 2018).

- Storage costs

Storage systems such as pumped-storage hydroelectricity or batteries enable to decorrelate electricity production and consumption periods. It requires both investments and operation and maintenance costs.

- Power services and operationalization costs

We include in this category all the costs that are required to make the system work in practice and that enable to improve it. It includes:

- New systems costs for real time load management through demand flexibility such as load shifting and shedding. Compensation costs to remunerate lost production for industry after load shedding are economic transfers between PS actors and thus should not be counted here (see Specific actors' perspective paragraph).

- Costs related to the wholesale and retail electricity markets functioning (aggregators, etc.)

- Commercialization costs related to the sale of produced electricity. It includes advertising, marketing and customer management costs. Some other costs can be borne by electricity providers depending on the rules of a specific country such as the purchase of energy savings certificates, but these are also economic transfers and thus should not be counted here.

- Transaction costs required for the changes to actually happen, that can appear at local scales for example such as costs for consultations, costs of transmitting information, etc.

- etc.

- Vector shifts

Some uses can be transferred from the electrical system to another system and vice versa thanks to vector shifts.

For example, some of the mobility previously provided by the oil system can be transferred to the electrical system via the introduction of the electric vehicle. This translates into an increase in demand for electricity and equipment such as electric cars and associated infrastructures in the power system inventory which may already appear in production and consumption sectors. At the same time there is a decline in fuel consumption and in the need for equipment in the oil sector. In order to count the net effect of this vector shift, these savings in oil sector can be taken into account by allocating the savings to the PS or by enlarging cost perimeter to the oil sector.

[3] For example there can be a tradeoff between investing into more transmission capacity and paying producers to increase/reduce their production or use more storage and demand flexibility, as reducing demand is equivalent to increasing the supply from a supply-demand balance perspective.

Recommendations for scenario producers

Method for accounting vector shift:

- Scenario producers should first make sure cost increase or reduction happening within the power system inventory is already appearing in production sector, consumption sectors, etc. in order not to count it twice. If not, it should be accounted.

- Cost increase or reduction happening in the other sector should be accounted to correctly take net effect into account, for example by allocating this cost variation to the PS or by enlarging cost perimeter.

- Consumption costs

The use of electricity requires all the steps to produce and deliver it when needed, but also the presence of all the appliances that actually make it possible to consume it as an energy service, such as light bulbs, heat pumps, electric vehicles, etc. Integrating the costs of power system demand-side implies to count the costs of every new consuming equipment as in PRIMES model (Capros, s. d.) or (Association négaWatt, 2017). It doesn't matter if each equipment comes in replacement of another old one or for a new usage; and it doesn't matter either if each equipment is more efficient. This way, investment in energy efficiency, appliances, heating systems, and related infrastructure (buildings, factories) throughout the economy are all taken into account.

NB: Considering energy system demand-side and not only energy system supply-side enables to consistently introduce energy efficiency measures. It can be a very cost-effective way to reach energy balance by reducing energy demand instead of increasing the supply. This framework enables to take such measures into account. However, as previously explained, the framework presented here cannot be used as it is for studies using the demand sobriety lever (i.e., a reduction of *human demand*, see Demand section). Indeed, a technical evaluation is not sufficient to make counterparties related to the demand sobriety lever correctly appear. An additional consistent macroeconomic analysis would be needed for that purpose.

- Climate change impact on costs

Climate change requires both adaptation work (e.g. the construction of dikes to protect infrastructure from rising water) and repair work (e.g. reconstruction of a high voltage line after a hurricane). Such impact can occur both for supply and demand-sides (see Consommation et Production sections)

NB: other impacts on costs than those related to climate change may also be taken into account.

Furthermore, we chose not to include externalities in the inventory. Indeed, we argue externalities are better counted when expressed in physical quantity rather than in costs (see Externalities paragraph).

D. Cost indicators: chosing the adapted metric according to what needs to be enlighten

The adapted choice and use of cost indicators for a consistent economic evaluation is the last element of this framework. This choice depends on the type of economic evaluation, the chosen point of view, and the system that has been defined. Thus, if the evaluation is of a macroeconomic nature, indicators such as GDP gaps should be used. The next part explores the possible range of indicators in the case of an economic evaluation of a technical nature.

Recommendations for scenario producers

Given the unclear nature of costs, the link between the used indicators and the conclusions drown by the scenario producer should be thoroughly substantiated. Each indicator should be used depending on what needs to be explored about the assessed system.

Which cost use is being explored? To what extent the proposed conclusions emerge from the chosen cost indicators?

IV. Cost indicators: a detailed review of how to compare and evaluate the costs from a system perspective, and some insights about specific actors' perspective

A. Comparing and evaluating the costs of scenarios from a system perspective: a table of system technical cost indicators and a focus on three indicators with specific uses

Once a clear system inventory has been defined, there is several ways to compare and evaluate costs of this given system.

We first propose a table to summarize the different cost indicators of a technical nature that can be used to assess costs from a system perspective. Each one of these system technical cost indicators can be expressed as a cost trajectory or a final cost value and can be composed of one to five cost items. This categorization brings transparency about the diversity of indicators that can be chosen depending on how and what scenario producers want to enlighten.

We then summarize good practices to follow when comparing scenarios. For example we explain that every scenario should be compared to a detailed reference scenario rather than to the current situation when informing public decision since today's cost is not an option in the future.

Finally, we focus on three specific system technical cost indicators and explore their respective uses:

- **"Expenses shape"** to visualize the evolution of costs that will effectively have to be paid during one scenario.

- **"Differential costs"** to properly compare two scenarios.

- **"Absolute costs"** to understand the costs evolution with today's cost.

We argue expenses shape and differential costs are viable indicators to enlighten public decision whereas absolute costs is useful for storytelling purposes only.

1. A table of system technical cost indicators to enlighten discussion

Once a clear system inventory has been defined (see Power system cost inventory), there is several ways to compare and evaluate costs of this given system depending on how and what scenario producers want to enlighten. We propose here a table categorizing the diversity of possible cost indicators of a technical nature (as opposed to macroeconomic indicators) that can be used to assess costs from a system perspective (as opposed to indicators designed from specific actors' perspective)[4] on the entire scenario timeframe.

Recommendations for scenario producers

Given the unclear nature of costs, the link between the used indicators and the conclusions drown by the scenario producer should be thoroughly substantiated. Each indicator should be used depending on what needs to be explored about the assessed system.

Which cost use is being explored? To what extent the proposed conclusions emerge from the chosen cost indicators?

[4] Depending on the system that is defined, it may happen that the system point of view matches a specific actor's point of view, such as the final consumers' perspective in the case of the s-LCOE indicator for example.

If the evaluation is of a macroeconomic nature, other indicators such as GDP gaps should be used.

In addition, it should be borne in mind that these indicators provide of course insights about the cost within the defined assessed inventory only. This is often not the entire system, and it can change from one study to another.

Here is the system technical cost indicators table:

Social discount rate if any	WACC if any	*Actual expenditures* cost items			Cost items for fairer comparisons	
		CAPEX *with or without capital costs*	+ OPEX	+ Electricity trade balance	+ Future costs	+ Past costs
Cost trajectory	*For one scenario*		s-LCOE	Expenses shape		Absolute costs
Cumulated value	*Difference between two scenarios*					
Final cost value *with or without social discounting*	*For one scenario*					
	Difference between two scenarios				Differential costs	

Figure 4: System technical cost indicators table

a. Key elements of the table

Some examples of indicators are presented in the table, but there are of course many others. Expenses shape, differential costs and absolute costs indicators are further described, and s-LCOE is described in LCOE section.

The two dimensions: five cost items and two types of indicators

Each indicator can be composed of one to five cost items. The five cost items are presented in detail in a dedicated section. There are two types of cost items: *actual expenditures* (columns one to three) are expenses that actually have to be paid each year during the scenario whereas cost items from columns four and five enable to integrate 'edge effects' for fairer comparisons (future costs enable better comparison between scenarios and past costs enable better comparison of a scenario with today's situation). The table is presented in such a way one cost item is added every column but cost indicators can of course be composed of every cost item presented alone (e.g. a fuel costs trajectory as in (Greenpeace, 2015) or an electricity trade balance trajectory as in (RTE, 2017)).

So as to express these system technical costs, two types of indicators are distinguished: cost trajectories and final cost values. The characteristics of these two types of indicators are presented in the following paragraph. In both cases, the indicator can be presented as an outcome for a single scenario or as a difference between two scenarios.

Use of discount rates

This table makes it possible to visualize where the notion of discounting can be integrated, and in the meantime to illustrate the difference in use between private and public discount rates.

On the one hand, integration of capital costs appears in the first column (CAPEX). Indeed, if a WACC is used in the calculations (see Discount rate section), then the cost of capital is implicitly included in the CAPEX column. If no private discount rate is used, the CAPEX cost item does not include any capital costs.

On the other hand, integration of a social discounting appears in the second line (Final cost value). Indeed, using a social discount rate section in the calculation of a final cost value[5] enables to assess costs from a benevolent planner point of view (see Discount rate section).

NB: once discounted with a social rate, the costs are no longer the initial costs since the discounting 'flattened' the value of the future. Thus, it can be noted that only cost indicators based exclusively on one or more *actual expenditure* cost items (columns 1 to 3) and which does not include a social discounting can indicate costs *as observed within the scenario timeframe*.

Both supply-side indicators and supply & demand-sides indicators

As explained previously, economic evaluations of a technical nature – including this system technical cost indicators table – are adapted both for supply-side studies and supply & demand-sides studies without demand sobriety. Thus, the table includes both indicators for evaluating scenarios based on a 100% supply-side inventory, including indicators expressed in €/MWh when the value has been divided by the demand, and indicators for evaluating scenarios based on an inventory including supply and demand-sides, with mainly indicators expressed in €.

b. Two types of indicators: cost trajectories and final cost values

There are two main types of indicators that provide information on the assessed system during the entire scenario timeframe: cost trajectories and final cost values. Both are widely used in future studies.

Cost trajectories are mainly useful for expenses visualization

Cost trajectories describe the evolution over time of one or more cost items. It is represented by a curve or a bar graph with a value for each time step (every year, every five years, etc.) Cost trajectories are represented for a single scenario most of the time, but can be sometimes expressed as a difference trajectory between two scenarios as in (Fraunhofer ISE, 2015) (see annex A for some examples).

Indicators such as s-LCOE (see LCOE section) or the further presented Expenses shape are cost trajectories.

This type of indicator can be used to:

- present the results of a single scenario, in order to visualize its cost trajectory.

- compare the results of several scenarios for evaluation purposes, typically to inform public decision (i.e., once the modelling and optimization work is completed and the final results are obtained). One criterion can be for example to look at the maximum expenditure value of the trajectory for several scenarios.

Most of the time, trajectories are used to visualize cost indicators based on *actual expenditure* cost items (CAPEX, OPEX, and Electricity trade balance), but it is also possible to present trajectories integrating cost items for a fairer comparison (future costs and past costs) as in (RTE, 2017).

In addition, applying a social discounting to a cost trajectory 'flattens' the costs and thus distorts the trend. Thus, when a cost trajectory indicator is presented it should not be discounted, except in rare cases (e.g., when highlighting the effect of a discounting over time, as in (Fraunhofer ISE, 2015)).

[5] A cost trajectory is not supposed to be discounted, except in rare cases as explained in the following section.

Thus, it can be considered that most of the time, cost trajectories allow to visualize costs *as observed within the scenario timeframe*.

Final cost values are mainly useful for cost comparison

Final cost values are unique values (i.e., a number) representing the cost of the assessed system over the entire scenario timeframe. It includes all the indicators commonly referred to as "total system cost" (European Commission, 2011; European Commission, 2016), "total cost of a pathway" (ADEME, 2015; ADEME / Artelys, 2018), "cumulative total cost" (Association négaWatt, 2017; Fraunhofer ISE, 2015). It is even sometimes referred to as "cost to society", as in (ECF, 2010).

In all these studies, what is expressed is the total technical cost of the studied system of a scenario. From one study to another, what changes is the inventory considered (system perimeter) as well as the cost items taken into account. It is in this final cost values category that the total CAPEX/OPEX of a scenario, or the further presented Differential costs indicator can also be found.

The final cost value of a system for a given scenario is obtained by summing all the costs taken into account, that is, by calculating the integral of the corresponding cost trajectory (same system, same cost items). A discount rate can be included in the calculation. If this is the case, then it must be a social discount rate (see Discount rate section). The final cost value obtained is then modified compared to a calculation without discounting[6], typically downwards in the case of a positive discount rate (which the case most of the time). These are not then costs *as observed within the scenario timeframe* that are expressed, but rather costs of the system evaluated from a benevolent planner perspective (see Discount rate section).

In any case, final cost value indicators can be used to:

- compare the results of several scenarios for selection purposes so as to obtain the final results of a study (i.e. during the modeling/optimization phase of the scenario exercise). For this specific use, many studies select optimal pathways using an objective function to minimize total cost, i.e., to minimize this final cost value indicator.

- present the results of a single scenario. However, final cost values are rarely presented alone and for a single scenario: the implicit purpose is very often to compare the values of several scenarios, even if they are not presented at the same place in the report. This brings us to the next use.

- compare the results of several scenarios for evaluation purposes, to inform the public decision once the final results are obtained. This is the most common way to compare scenarios. For this purpose, we argue that **"future costs" cost item** allows to correct the comparison biases due to the horizon effect but is too often neglected in future studies (see Future Costs paragraph). In other words, when final cost values are used to compare scenarios when presenting results, the comparison is fairer if the indicator falls in column four of the system technical indicators table. The further presented Differential costs indicator is typically designed in that way.

NB: to properly use cost indicators for comparison purposes, see the further presented Set of recommendations about cost comparison between scenarios.

In addition, as for cost trajectories, final cost values can be represented for one single scenario or as a difference between two scenarios. Comparing scenarios using a differential value has an advantage: in addition to negligible cost elements, it enables to also neglect elements with little cost difference between scenarios. Indeed, if the possible evolution of the costs is the same from one scenario to another, then the value in difference remains unchanged and the comparison remains fair. In this way, (RTE, 2017) for example neglects part of the commercialization costs when comparing several scenarios.

[6] Or with a 0% discount rate.

2. Set of recommandations about cost comparison between scenarios

We explained in Power system inventory section that the assessed perimeter should be both similar and sufficient for a good comparison. Here are other recommendations for fair comparisons, with a summary at the end.

a. A scenario should not be compared to today's cost when trying to inform public decision: comparing a future to a present is indeed only viable for storytelling purposes only

It is quite common and intuitive to try to compare the costs of a given scenario to the costs we are experiencing today. However this is a bad practice to inform public decision since current situation is not an option in the future: a future can only be compared to a future.

Comparing a future to a present can be useful, but for storytelling purposes only.

For example if the reference scenario of a future study leads to a tripling of the costs of the assessed system, choosing not to select a scenario leading to a doubling of these costs because it is more expensive than today would be a poorly informed decision.

As explained in DECC 2050 Calculator documentation (« Costs methodology for 2050 Calculator », s. d.): *"Pathway costs should be understood relative to other pathways. The total cost of pathways is presented in the 2050 Costs Calculator but for these to be meaningful they should be compared to the costs of another pathway. This is because there is no "zero cost" option (unless the UK were to stop using energy altogether)."*

(Agora Energiewende, 2015) also support the same idea.

b. Scenarios should rather be compared to a detailed reference scenario

The only way to perform a proper scenario comparison is to compare several future options. To do so, a future study has to include one reference scenario. This is the case most of the time. This reference scenario should ideally be as detailed as other scenarios. It can be a BAU scenario but it is not necessarily the case.

Est-ce qu'on a des compléments sur ces histoires de BAU ? ou une section à laquelle faire référence ici ?

When trying to evaluate a transition scenario (e.g. when trying to answer the question "What is the cost of the proposed transition?"), the reference scenario should be a BAU one so as to understand what are the implications of choosing the transition scenario over a non-transition pathway. Again, this is the case most of the time.

> Recommendations for scenario producers
>
> A scenario should not be compared to current situation when trying to inform public decision as current situation is not an option in the future. It should be compared to a detailed reference scenario instead.
>
> When trying to evaluate a transition scenario, the reference scenario for comparison should be a BAU scenario with a clear definition of what is included in this scenario (e.g. a BAU scenario following these guidelines).

c. When comparing two systems, the chosen cost indicator should be sufficient

As for inventories, a cost indicator needs to cover all the changing elements between two systems so as to compare them fairly. To do so, all the cost items evolving differently from a scenario to another should be included in the calculation of the chosen indicator.

This is particularly true with future costs, which are costs and savings that will happen beyond the end date of a scenario due to choices that occurred within the scenario timeframe. This cost item should be included so as to take horizon effect into account for fairer comparisons. (see Future costs paragraph)

Recommendations for scenario producers

The chosen cost indicator for comparison between two scenarios should be sufficient: it should include all the cost items evolving differently from a scenario to another. It should typically include the often neglected 'future costs' cost item so as to correct comparison biases due to horizon effect.

d. Summary of the method for comparing scenarios

As illustrated previously, properly comparing two scenarios may require more attention that it would seem. Here are the key points to keep in mind when trying to inform public decision through a cost comparison.

- Similar inventory: the evaluated systems should have the same perimeter.

- Sufficient inventory: the evaluated systems should include in their perimeter all the subsystems evolving differently from a scenario to another.

- Reference scenario: only future option should be compared since today's cost is not an option in the future. Transition scenario should be compared with a BAU scenario.

- Adapted cost indicator: the type of indicator should be chosen according to what is compared. Is it the expenses year after year or the overall extra cost over the whole period?

- Sufficient cost indicator: the chosen cost indicator for comparison should include all the cost items evolving differently from a scenario to another, especially future costs.

- Social discount rate: costs can be discounted over time. If so, a social discount rate should be used.

Following these recommendations enables for example to better answer to an intuitive and often asked question: *"What is the cost of transition?"* To do so, the given transition scenario should be compared with a BAU scenario. Both scenarios should be based on a clearly defined similar and sufficient perimeter, typically a perimeter including adaptation and repair costs due to climate change. The chosen indicator should be a final cost value expressed as a cost different between the two scenarios so as to compare the overall extra cost over the whole period, and should include CAPEX, OPEX, electricity trade balance and future costs so as to be sufficient. A social discount rate can be included in the calculation.

This is typically what the further presented differential costs indicator is designed for.

3. Three specific system technical cost indicators and their respective use: expenses shape, differential costs, and absolute costs

As an illustration of what has been previously developed, we provide here a clear definition of three specific system technical cost indicators with discussion about their uses. They all aim at evaluating system costs in different ways:

- **"Expenses shape"** shows the time evolution of a scenario expenses *as observed within the scenario timeframe*. It enables to visualize the actual financial effort that will have to be made year after year.

- "Differential costs" is the difference in cost between two scenarios, including costs and savings occurring after the end date of the scenarios. It enables to properly compare two scenarios. We argue this indicator is well designed to discuss the "cost of transition" in a relevant way.

- "Absolute costs" shows the time evolution of the costs of one scenario, including costs and savings occurring before and after the end date of the scenarios. It enables to understand the costs evolution with today's situation.

Expenses shape and differential costs are viable to inform public decision whereas absolute costs should be used for storytelling purposes only.

a. Expenses shape: the cost trend of one scenario

Expenses shape is a cost trajectory for one scenario. It shows the expenses evolution of the assessed system through time *as observed within the scenario timeframe*.

To that end, this indicator includes the three *actual expenses* cost items and only those three (CAPEX, OPEX and electricity trade balance) and the shape should not be discounted.

Adding future or past costs would indeed add costs that will not effectively be paid during the scenario[7], (see Cost items section for more details) and the use of a discount rate would 'flatten' the costs and thus distort the trend.

Thus, expenses shape describes the evolution of the expenses through time *as observed within the scenario timeframe* each year.

Expense shape of one scenario gives interesting information about the overall effort repartition. It can reveal key information such as expenses peaks during the scenario timeframe. Furthermore, expenses shapes from two different scenarios can be compared, for example to see which one has the highest maximum annual cost value.

When each of the three cost items appears distinctly within the expenses shape (i.e. when the indicator is clearly subdivided into CAPEX, OPEX and electricity trade balance) it provides information about which specific actor will bear the costs. For example the CAPEX part of the shape is useful to measure the overall financial effort that has to be performed to develop and extend capacities, and possible difficulties related to the corresponding fundraising.

As the three considered cost items can differ significantly from a scenario to another, we believe expenses shape is an important indicator to inform public decision.

b. Differential costs: the good value when comparing two options

Differential costs indicator is a final cost value difference between two scenarios. It is designed to enable a fair comparison of the two given scenarios.

As explained in the Recommendations for comparison section, this indicator is well designed to express a 'cost of transition'.

To that extent, it is composed of four cost items, namely CAPEX, OPEX, electricity trade balance and future costs. Adding future costs enables to make a good comparison by handling what can be sometimes called "horizon effect". Indeed, as differential costs indicator corresponds to the cost difference between two scenarios it is important to compare their costs fairly. Past costs are not useful here because they would not change the value of the difference. (see Cost items section for more details)

This is why differential costs can be considered as a good 'cost of transition' indicator when comparing a transition scenario to a BAU scenario.

Differential costs can include a discounting, using a social discount rate, to express costs from a benevolent planner perspective. (see Discount rate section)

In the end, this means that differential costs between two scenarios can be calculated from the expenses shapes of these two scenarios through four steps: discount each expenses shape, add the corresponding discounted future

[7] Or remove costs that will effectively be paid during the scenario.

costs, make the integral of both resulting cost trajectory, and finally do the subtraction (see more explanations in Future costs paragraph).

Some studies use this cost indicator such as (Fraunhofer ISE, 2015) or (IRENA, 2018), under the name of "differential costs" or "additional cost" in order to compare two trajectories. In both case, a reference trajectory and a transition trajectory are compared. Conclusions are drawn about the "extra cost" of the transition scenario over the reference scenario, so as to answer the question "What will the energy transition cost?" or to compare these extra costs with the benefits of a transition pathway.

However future costs are not necessarily included which can be a caveat since horizon effect is neglected.

c. Absolute costs: comparing the future with today for storytelling purposes

Absolute costs indicator is a cost trajectory of one scenario. It is a trend that enables to understand cost evolution of the assessed system from today**'s situation**.

Unlike the expenses shape, this indicator does not represent the costs that will actually have to be paid each year. It rather represents the cost of the assessed system including 'edge effects' by adding past and future costs to the three other cost items. By doing so, it enable for example to take into account the costs of assets used within the scenario timeframe that were already in place (see Future costs and past costs paragraphs in Cost items part).

Thus this indicator is composed of all five cost items, and does not include a discounting. These are therefore the "absolute" costs of the assessed system. Such indicator enables to properly compare the cost of a future situation with today's situation. However, as already explained, only future situations can be consistently compared for decision making. Therefore absolute costs indicator should not be used for public decision but for storytelling purposes only.

For example in can help to understand how the importance of the assessed system (e.g. electricity sector) is changing over time from today compared to other sectors (in terms of share in the aggregated cost) and thus how it would "feel" in the future to live in the scenario.

B. Assessing costs **from specific actors' perspective**: complementary insights through cost indicators such as price/cost of energy

1. **Specific actor's perspective can bring complementary insights and** can occasionally match system perspective

As previously explained, assessing costs from a system perspective should be preferred to inform public decision, but specific actors' perspective also bring useful complementary insights. It may be indeed interesting to assess costs from an electricity producer perspective, from the government perspective, or from the perspective of households or industries so as to enlighten issues related to bankability or purchasing power. As explained in the next part, assessing costs from a specific actors' perspective requires to take extra elements into account (see Economic transfers paragraph).

It should be noted that in particular cases, system perspective can be very close, or even match a specific actor's perspective. It happens only with indicators describing costs *as observed within the scenario timeframe,* that is, cost indicators that do not include any social discounting in the calculation and which are based exclusively on *actual expenditures* cost items (CAPEX, OPEX, and/or electricity trade balance). In addition, capital costs should be included in CAPEX. This is for example the case of the s-LCOE indicator (see LCOE section). Thus, if the assessed system takes into account the entire supply-side of the power system cost inventory, then the s-LCOE (which is a system technical cost indicator) can at the same time be adapted to enlighten the final consumer's point of view (excluding tax).

2. *Cost* of energy better informs the debate than *price* of energy for final consumers, and both indicators require special care

NB: This paragraph deals with the price and cost of energy for final consumers and not price and cost of electricity only for final consumers since the reasoning is valid in both cases.

The distinction we make between these two indicators is that price of energy is a value expressed in €/MWh while cost of energy is expressed in €.

Price of energy for final consumers is often considered as an important criteria

On the one hand it can be an important criteria for households from a social desirability and energy poverty perspective. For example, some polls indicate that very few French people would agree to see energy price increased by 20%. (Percebois, s. d.) On the other hand this also concerns industries, which consume energy for their production.

Thus, it is often argued that the price of energy plays a major role in our economy: all things being equal, an increase in energy prices in a country reduces the purchasing power of households and the "competitiveness" of companies. (Percebois, s. d.)

This argument is true, but it would be wrong to infer that any measure reducing energy price would be a good one. To understand why, system as a whole has to be considered: supply-side but also demand-side.

A more complete indicator would be the *cost* of energy for final consumers

Indeed, what households and industries are really interested in is not the price of energy - although it may seem intuitive - but its cost, that is, the final bill actually paid at the end of the month. Therefore it is the energy cost variations that makes it possible to understand how the purchasing power or competitiveness varies.

For example, if an energy efficiency measure that increases the price of energy reduces consumption enough to make the final cost decrease, then it may be judged as a good measure[8]. The implicit final goal is never to minimize the price but to minimize the cost.

Recommendations for scenario producers

Energy cost indicator should be preferred over energy price indicator when possible so as to better inform the debate. Cost better informs about purchasing power and competitiveness evolution since it represents the final bill paid at the end of the month and thus enables to take into account trade-offs between lowering the price and reducing demand.

The choice between *price* and *cost* of energy depends on the type of study

As previously presented, we define three main categories of studies, according to the levers activated to ensure the balance between supply and demand (see Three categories of study paragraph).

Energy price indicator (€/MWh) is better adapted for supply-side studies (i.e. studies using levers on the supply-side only), while the use of an energy cost indicator (€) becomes appropriate for supply and demand-sides studies (with or without demand sobriety).

As most studies are supply-side studies, the energy price indicator is most often calculated. Energy cost indicator is for example calculated in (Fraunhofer ISE, 2015). The method used is to calculate the "yearly cost for end consumer" as a whole (not per person) which consists in the sum of total system costs plus some taxes. This is the global common effort to share between all end consumers.

The use of both indicators requires special care, especially when trying to compare them **with today's** price/cost of energy

As any other indicator, energy price and cost indicators can be used to compare several future options or to compare a future option with today's situation. Furthermore, both indicators can be *partial* or *complete*. To be *complete,* an energy price indicator should be based on the overall supply system while an energy cost indicator should be based on the overall supply and demand system. Otherwise, energy price/cost indicators are *partial*, since they only refer to a *fraction* of the overall system.

When comparing the energy price/cost of several future options (i.e. of several scenarios), it doesn't matter if they are *complete* or *partial*. What matters for a fair comparison is that the system perimeter is similar and sufficient (see Recommendations about cost comparison paragraph).

However in practice, these indicators are often used to compare energy price/cost of a given scenario to today**'s** energy price/cost (directly or indirectly) because these indicators are closely related to **people's daily life**.

In this case, a first elements to keep in mind is that comparing a future to a present is only useful for storytelling purposes and should not be used to inform public decision since today's situation is not an option in the future (see Recommendations about cost comparison paragraph).

Secondly, the scenario energy price/cost indicator should be *complete* to enable a fair comparison since today's energy price/cost are by definition *complete* indicators. Thus, it requires to take into account the overall supply/supply and demand system, which is not often the case in future studies: the distribution component is for example often forgotten. Furthermore, today's energy price/cost often include taxes and subsidies (e.g., one third of the electricity bill for households in France is composed of taxes). It means a fair comparison with today's situation requires to make some (strong) assumptions on future political decision such as taxes and subsidies

[8] It is the case because energy efficiency does not consists in reducing energy service demand. It enables indeed to reduce energy supply with a constant energy service demand (see Energy consumption file)

systems. Thus, price or cost of energy can be more influenced by choices in the Storyline than by evolution in the scenario itself.

If the energy price/cost indicator is *partial* (i.e. it refers only to a *fraction* of the energy system), then the only possibility for a fair comparison with today's situation is to compare it with the corresponding *fraction* of today's energy price/cost. In the same way, it is possible to compare a scenario price/cost of energy *before tax* with today's price/cost *before tax*. In this case, it is particularly important that the perimeter of the comparison is clearly described and the conclusions drawn from this analysis are justified with regards to this perimeter.

Recommendations for scenario producers

When using an energy price/cost indicator in an economic evaluation to provide insights from a specific actor's perspective, the assessed perimeter behind these indicators should be clearly defined and the integration or not of economic transfers should be made explicit.

Is the given energy price/cost indicator based on the overall supply / supply and demand system? Or do they only refer to a fraction of the overall system? Which fraction? What assumptions are made about taxes or subsidies taken into account?

When an energy price/cost indicator is used to make a comparison with today's situation (which is often the case), it should be made explicit that such analysis is only viable for storytelling purposes (and not for informing public decision). In addition, the used indicator should be based on the overall supply / supply and demand system (the distribution component is for example often forgotten) or it should be compared to today's corresponding *fraction* of the system with a clear justification of how conclusions drawn from this analysis are justified with regards to this chosen perimeter.

C. The five possible cost items to build system technical cost indicators

This section describes the several cost items than can be used to calculate system technical cost indicators:

1 – CAPEX
2 – OPEX
3 – Electricity trade balance
4 – Future costs
5 – Past costs

The following description of the five items is designed to assess costs from a system perspective. To build specific actors' cost indicators, the same five cost items can be used, but new elements should be added, as explained in the Economic transfers paragraph.

Here is a summary of how to assemble the cost items to calculate the three previously described system technical cost indicators:

	Expenses shape	Differential costs	Absolute costs
CAPEX	Y	Y	Y
OPEX	Y	Y	Y
Electricity trade balance	Y	Y	Y
Future costs	N	Y	Y
Past costs	N	U	Y

Y : Yes N : No U : Useless

Figure 5: Cost items composition of the three presented system technical cost indicators

Reading key: expenses shape must include CAPEX, OPEX and electricity trade balance and must not include future and past costs. Past costs can be accounted for differential costs but are useless: it would not change the result.

1. Introductive remarks about the cost items

The first two cost items (CAPEX and OPEX) are almost always accounted in future studies while the three others are often neglected. We explain in next paragraphs why electricity trade balance and future costs are particularly important to consider and how future costs also enable to take sunk costs into account.

The five cost items can also be divided in two categories: CAPEX, OPEX and electricity trade balance are what we can call *actual expenditures*, i.e. expenses that actually have to be paid each year during the scenario; whereas future costs and past costs are cost items enabling better comparisons by integrating edge effects.

In addition, calculations of some of these cost items may require to annualize them, that is, to allocate a one-time cost over several years. Several annualisation methods exist. For example, a 20M€ expenditure useful for 10 years can be distributed "on average": 2M€ per year over 10 years. But it could also be progressively discounted and/or indexed on inflation.

Recommendations for scenario producers

The chosen annualisation method should be explained for more transparency.

What is the reference period for annualisation? Is it the technical service life of a plant? Are cost equally distributed over the period? Are costs also discounted in the same time? Is inflation taken into account?

2. Description of the five cost items and their specificities

The five items presented here are designed to assess costs from a system perspective. Therefore, no economic transfers between specific actors should be included.[9] For example, all cost items should be tax free to avoid distortions due to different tax levels for different products or services. To assess cost from specific actors' perspective, see the following Economic transfers paragraph.

NB: note that all those costs depend ultimately on labour costs which depend on local tax, environmental and social regulations, and on import and export costs.

[9] Or both 'sides' of each economic transfer has to be included so that the value is cancelled in the sum.

a. CAPEX

CAPEX (Capital Expenditure) is composed of all the investments, such as investments to build new capacities, extend the life of already existing capacities, or spare money (provision) for future expenses as dismantling or waste management.

Depending on the scenario producer choice, capital costs may or may not be included. Capital costs are the financing costs of the investments. They are included in the calculation whenever a WACC is used (see Discount rate section).

b. OPEX

OPEX (Operating Expenditure) comprises all costs required to make the system operate. It includes fixed costs such as worker wages and regular maintenance operations of infrastructures, and variable costs such as the purchase of fuel to make power plants run. Carbon quotas on EU ETS market, taxes, and other economic transfers should not be included as these are not costs from a system perspective: they are not needed to make the system operate and should therefore only be considered when assessing specific actors' perspective (see Economic transfers paragraph). Here is a summary of how to handle externalities in economic evaluation, see Externalities section for more details.

> Handling externalities when presenting the results of a scenario
>
> Putting a price on externalities is a controversial approach since it is considering that the related impact is linear (e.g., 50 tons of CO2 are considered 50 times worse than one ton of CO2) although it is clear that environment reaction to such pressure is definitely non-linear. Environmental thresholds indeed imply that the 40 first tons of CO2 could have a small impact while the 10 last tons could have a huge impact by making a system switch in another state.
>
> Thus, for economic evaluation from a system perspective, we argue it is preferable not to express externalities in terms of costs and rather present them as physical quantities in a multi-criteria dashboard (this is different from a specific actor's point of view, see corresponding paragraph).
>
> However if the scenario producers prefers to include externalities in the scope of the costs when presenting results from a system perspective, the only viable option to include them fairly from a system perspective is to choose an appropriate shadow price. For example, choosing to express CO2 externality when presenting the results by attributing an EU ETS carbon price to it would be a huge underestimation of its real negative impact.

c. Electricity trade balance

Electricity trade balance is the net cost or revenue due to electricity imports and exports with neighbors[10].

As it can be significantly lower than CAPEX and OPEX, it may be justified to neglect its value in some cases. However, as pointed out in (RTE, 2017) it can also be an important item, that can vary significantly among scenarios (going from a positive to a negative value in some cases and going from the same positive value to a tripling in others).

What must be taken into account here are the exchanges between countries within the geographical scope of the scenario and the countries outside. Exchanges among countries within the geographical scope are indeed only an economic transfer in the scenario and do not have an impact on the overall costs or revenues. It would enable to provide insights from actors' points of view but should not be accounted as a system cost. Thus, in the proposed framework, electricity trade balance does not need to be assessed in worldwide scenarios since there is no neighbors "outside the geographical perimeter".

[10] It should not be seen as the overall trade balance of the electrical system (it does not contain imports of equipment for example).

Calculation method

Cost of imports and revenues from exports have to be calculated separately as the electricity price is not the same in the two situations. This is the case because imports and exports does not occur in the same time while the electricity price can significantly vary over time. One possibility used in (Fraunhofer ISE, 2015) is to set one unique purchase price for electricity import and one unique selling price for electricity export (expressed in €/MWh). Conservative values can be chosen so as to be sure the scenario remains robust. Hourly electricity price variation can also be taken into account for more accuracy.

Precaution of use in scenarios

A few elements should be borne in mind when planning to introduce electricity trade balance in a scenario, as described in Boundary Condition section. Countries' electricity trade balance should be justified to several extend:

- Import-export previsions must be **consistent with the neighbors' own previsions** (two neighboring countries cannot be net exporters toward the other in the same time).

- Thus geopolitical aspects are involved since neighboring countries or regions have to accept to be structurally importers or exporters, sometimes for several decades. This can be reported in the storyline.

- Time repartition of electricity exchange should be taken into account. For example if two neighboring countries have an important wind capacity, correlation in time between their electricity productions should be assessed. Moreover, if one of the two countries plans to import electricity during its peak hours, the real time ability of the neighboring exporter country to export electricity should be checked since it can be facing its peak hours at the same time. Annual import-export means are therefore not enough: hourly exchange capacities are needed. It implies to take a look both at supply and demand time repartition (especially in high RES mixes for supply).

- Interconnection capacities must be available so as to physically transport the electricity exchanges

(Fraunhofer ISE, 2015) takes electricity trade balance into account and handles some of these elements. This results in setting a maximum exchange power value in each of its scenarios (15GW in one case, 40GW in another, etc.)

d. Future costs

Future costs are the costs and savings that will happen beyond the end date of a scenario due to choices that occurred within the scenario timeframe. This is sometimes called the "horizon effect".

As we will see, integrating future costs enables both to properly compare scenarios and to take sunk costs into account.

Illustration

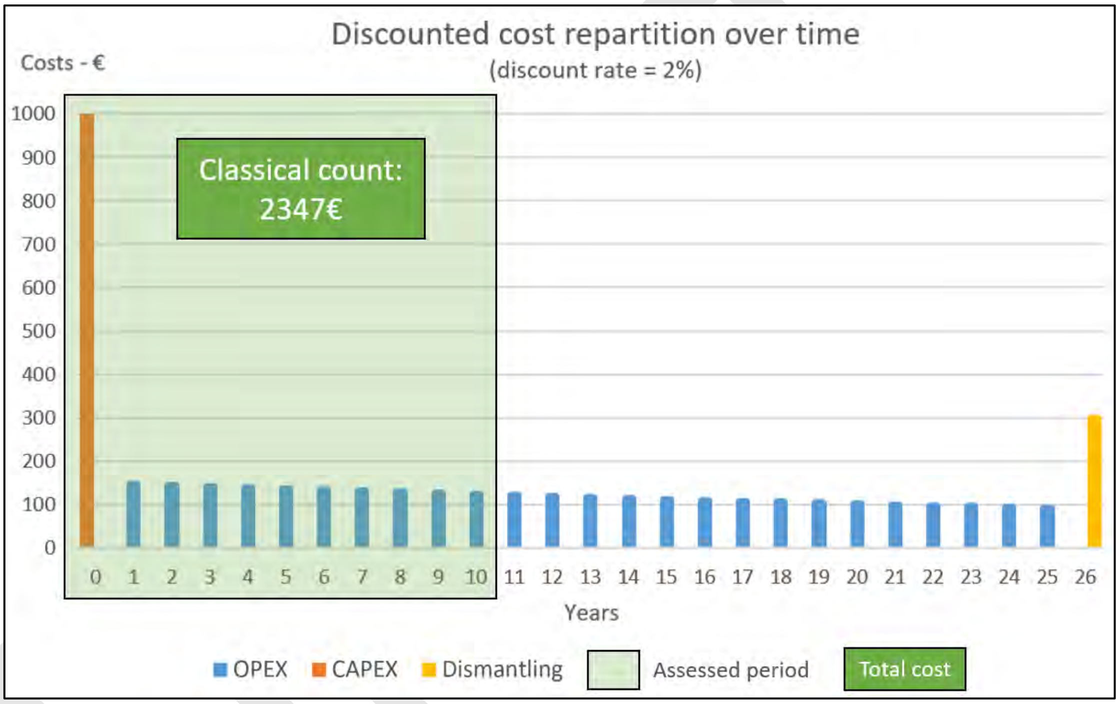
Let's take the example of a scenario A where a new hydropower plant is built one year before the scenario end date (let's say in 2049). All the CAPEX are paid in 2049 and the plant is used only one year in this scenario. But in fact it will produce low cost electricity long after 2050. Thus, all this 'unused CAPEX' can be seen as future savings. All these futures savings must be accounted so as to properly compare costs of scenario A with costs of a scenario B where the new hydropower plant is not built. Indeed, a *fair* **comparison requires to look at 'useful' CAPEX** (i.e. CAPEX which is actually used within the scenario timeframe) rather than total CAPEX. This is particularly important when comparing a BAU scenario with a transition scenario where big amount of high CAPEX and low OPEX decarbonized production units are deployed.

A *fair* comparison also requires to look at undervalued or unaccounted costs like dismantling or waste management costs that are due to choices occurring during the scenario timeframe but that will have to be paid after the end date of the scenario. Again, only the **'useful part'** of those costs must be taken into account. In this case, these are not savings but costs.

This is why this section could be named "future costs and savings" but we will keep the shorter "future costs" designation.

Since future costs will not have to be paid during the scenario period they should not be included in cost indicators aiming at describing costs *as observed within the scenario timeframe* such as the expenses shape indicator (see Expenses shape paragraph). Future costs are indeed not *actual expenses.* However they are required to compare several scenarios properly so as to get a fair comparison. They enable indeed to take "horizon effects" into account. This is why it is included in the differential costs indicator (see Differential costs paragraph). For example, the comparison between (RTE, 2017) four scenarios is better informed thanks to the integration of future costs according to RTE.

Here is an illustrative example: a 25 years lifetime asset has a 1000€ CAPEX with 150€ OPEX each year and a 500€ dismantling cost. The costs are discounted with a social discount rate of 2%. The scenario ends after the 10th year. Each of the two graphs illustrate a way of counting: classical way and including future costs.



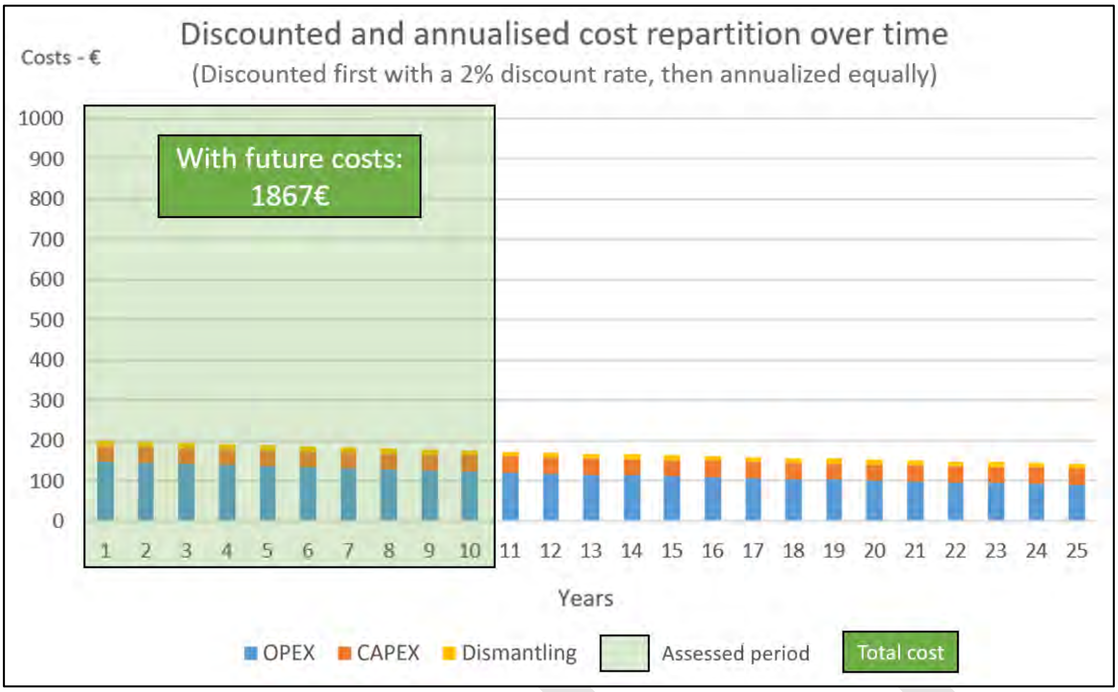


Figure 6: Illustrative example of counting with future costs

We can see that in the first case all the CAPEX are counted while dismantling costs are not taken into account. In the second case, future costs are added (and savings are removed): only the useful part of CAPEX is accounted, and the useful part of dismantling cost is added. The first method reflects the real discounted evolution of expenditures over time while the second method enables fairer comparisons.

Calculation method

Integrating future costs due to CAPEX still useful after the end date of the scenario consists in *removing* the **discounted 'unused' CAPEX**. Integrating future costs due to undervalued or unaccounted costs due to choices during the scenario timeframe that will cause costs after the end date of a scenario, such as dismantling costs, consists in *adding* **the discounted 'useful' part of those costs**.

Evaluating the 'unused' or 'useful' part of a cost: rule of three

RTE suggests two methodologies to evaluate the 'useful' part of a cost. Both examples are based on CAPEX, but the reasoning is the same for investments like dismantling costs.

The first one is the most simple and we believe it is efficient enough. It consists in counting only the CAPEX part used during the scenario period, thanks to an elementary rule of three. For example, if a wind turbine farm with a 30 years lifetime and 120M€ CAPEX was built in 2040 in a scenario that ends in 2050, only 10 years upon the 30 years should be counted which means that only one third of the CAPEX is counted. In this case, the CAPEX value of the wind turbine farm would be 40M€. More specifically, integrating future costs would consist in *removing* an 80M€ cost from the scenario total costs.

The second method consists in evaluating an "end-of-period value" for each type of capacity. This value reflects the real value the asset will provide between the final date of the scenario and the end of their lifetime. While the first method was a *time* pro rata, this one is a *real use* pro rata and would require specific additional hypothesis.

Introducing the discounting: discounting before adding

As any other costs, future costs have to be discounted. In order to properly add future costs while using a discount rate, these future costs must be discounted before being added.

Indeed, if they are added to other costs (for example to an Expenses Shape) without a discounting and then the resulting trajectory is discounted, no difference in value will appear between the future costs occurring at the beginning or at the end of the trajectory.

Thus, it is necessary to first discount future costs, then to distribute them year after year, and finally to add them to an already discounted cost trajectory. The discount rate used must be the same, and it has to be a social discount rate.

To sum up and give an example, going from two expenses shapes of a scenario A and a scenario B (see Expenses shape paragraph) to a differential costs between the two scenarios (see Differential costs paragraph) consists in:

- calculating and discounting future costs separately, with a social discount rate (let's say 2%)

- discounting each expenses shape with this same social rate (2%)

- adding future costs A to expenses shape A, and future costs B to expenses shape B

- summing the costs over the entire resulting cost trajectories, for A then for B

- subtracting these two values. The resulting value is the differential costs including future costs.

Future costs handle sunk costs

Integrating future costs enable to implicitly take sunk costs into account.

Indeed, if a plant is closed and replaced n years before its economic lifetime, the plant coming in replacement will arrive n years in advance and will therefore lose the value of these n years in the future costs account.

Let's take the example of a scenario A where a still-usable gas power plant is replaced by a new gas power plant in 2030 against a scenario B where the same replacement occurs in 2040. Without the integration of future costs, both scenarios have roughly the same costs over the period up to 2050 (i.e. gas purchase for the same number of years and CAPEX for the same new gas plant). But when the future costs are included (i.e. when only 'useful' CAPEX is accounted) scenario B becomes less expensive than scenario A since the new gas plant is 10 years "younger" in scenario B and will therefore be able to produce electricity 10 more years after the end date of the scenario. The cost difference between the two scenarios is the value of the sunk costs.

Another effect with lower impact is that the new gas power plant in scenario B benefits from a 10 years technology improvement with the associated cost reductions compared to the scenario A plant. This effect is also implicitly taken into account.

This method to include sunk costs into a comparison is efficient from a system perspective. However assessing the cost from specific actors' point of view also requires to identify who is going to pay for these sunk costs (see Sunk costs paragraph in Desirability section).

e. Past costs

Past costs follow a similar philosophy as future costs: they are the costs to be paid and the savings realized during the duration of the scenario that are due to expenses or decisions made in the past (i.e. before the starting date of the scenario).

It includes costs such as the dismantling of power stations or waste management, but also and mainly all the CAPEX of already existing infrastructures: we usually count the OPEX of these assets but not their CAPEX. As for future costs the idea is to integrate the 'scenario-useful part' of these CAPEX, which are not *actual expenses* (nobody will pay today for CAPEX already paid in the past). Therefore, past costs should not be integrated in cost indicators aiming at describing costs *as observed within the scenario timeframe.* Furthermore, past costs are a consequence of decisions that happened in the past, therefore they are the same for every scenarios using the same cost inventory. Thus, it is not useful to introduce these costs when comparing two scenarios since it would not change the differential value.

In the end, this cost item is only needed when trying to compare the costs of a scenario to today's cost, as with the absolute costs indicator (see Absolute costs paragraph).

Past costs can be calculated the same way that future costs with a time pro rata, but this time by *adding* the useful part of the past CAPEX. However it requires some specific assumptions with potentially high uncertainty.

3. Economic transfers needs to be added when assessing costs from **specific actors' perspective**

When choosing to evaluate the costs from a specific actor's point of view, new elements must be added: these are money transfers between actors.

We present here some of these economic transfers. This list in not comprehensive: many other economic transfer between actors can be added to the analysis (such as the purchase of energy savings certificates within commercialization costs or electricity trade balance between countries within scenario geographical scope for example).

- Taxes and subsidies

Taxes and subsidies are money transfer between actors. It does not constitute a real cost from a system perspective but actually is an expenditure and revenue for specific actors. It can be paid by the end consumers to the State for example.

- Internalized externalities

This term designates externalities that are actually paid like CO2 emission under EU ETS system. This is currently the case for a few externalities only, and the price paid does not necessarily reflect the real damages. This is another type of money transfer since power producers have to pay the State for their CO2 emissions but these emissions in themself do not require any additional jobs[11] or wages (it is thus not a real cost from a system perspective). The real system cost due to CO2 emission are related to climate change impacts and are not correctly reflected in EU ETS carbon price. We explain later how we think externalities should be accounted (see Externalities paragraph). Furthermore, when evaluating macroeconomic impacts, expenditures for taxes or quotas are sometimes accounted without considering their reuse by the State. Thus, income from internalized externalities should not be forgotten when trying to get insights such as bankability or purchasing power for some specific actors.

- Sunk costs burden sharing

Eventhough sunk costs are taken into account when calculating future costs (see Future costs paragraph), it does not indicate who is going to pay for it. This information is not important from a system point of view, but is needed to understand interactions between actors (e.g. some scenarios might put into play States compensating for sunk costs).

- Curtailment costs burden sharing

Curtailed electricity is also already included implicitly in the power system inventory: it appears indeed in production costs, network costs and storage costs, often as an optimization (the choice to curtail a part of the production can typically increase production costs while decreasing network and storage costs even more). However the same question of "who will pay for it?" can help to understand the actors' point of view. It can be particularly true in high renewable share mixes.

[11] These are not the job-creating investments driven by the tax signal to reduce emissions.

V. Externalities: physical quantities are more valuable than prices

Putting a price on externalities is a controversial approach. We prefer not to include externalities in the scope of costs and present them as physical quantities in a Dashboard instead. However if the scenario producers prefers to convert externalities in costs, the only viable option from a system perspective is to choose an appropriate shadow price.

Furthermore, concerning internalized externalities:

- It has to be considered when studying actors' point of view.
- Income from the taxes or quotas should not be forgotten when evaluating macroeconomic impacts.

A. Internalizing externalities is a tool to integrate them in economic decision making

Externalities are all the elements resulting from an activity that do have impacts which are not taken into account in the agents' economic calculations and therefore in their decision-making. They can be positive but are negative most of the time.

Externalities perimeter can possibly be very wide. Indeed, all environmental and sociopolitical aspects may be concerned: GHG emission (climate change), premature deaths, injuries, and illnesses (human health), loss of biodiversity, land use change, nuisance from noise and odor, congestion, or visual blight, impacts on energy security, geopolitical relations, family values, etc. (Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012)

There are several mechanisms for "reintegrating" an externality into decision-making. The main mechanisms are taxes, quota markets, regulation and subsidies. They enable to "internalize" the externality. This makes it possible to make the investments that reduce the externality profitable, and thus accelerate the change towards activities where the externality is reduced.

B. Internalized part of an externality is often not externality as a whole

However, in practice it is very complicated to fully internalize externalities. In fact it would require in the same time to choose both the scope that covers the whole problem (e.g. the EU ETS mechanism only takes into account tons of CO2 emitted by some activities but not all of them) and a price reflecting "the true value" of the real damage caused by the externality[12] (the price of CO2 on the EU ETS market is much lower than this "true" value).

Thus, we will distinguish here **"externality"** and **"internalized part of externality"**. The first one is the externality as a whole, while the second one is the price actually paid in the real world by the concerned actors for the given externality.

[12] This is called a "shadow price"

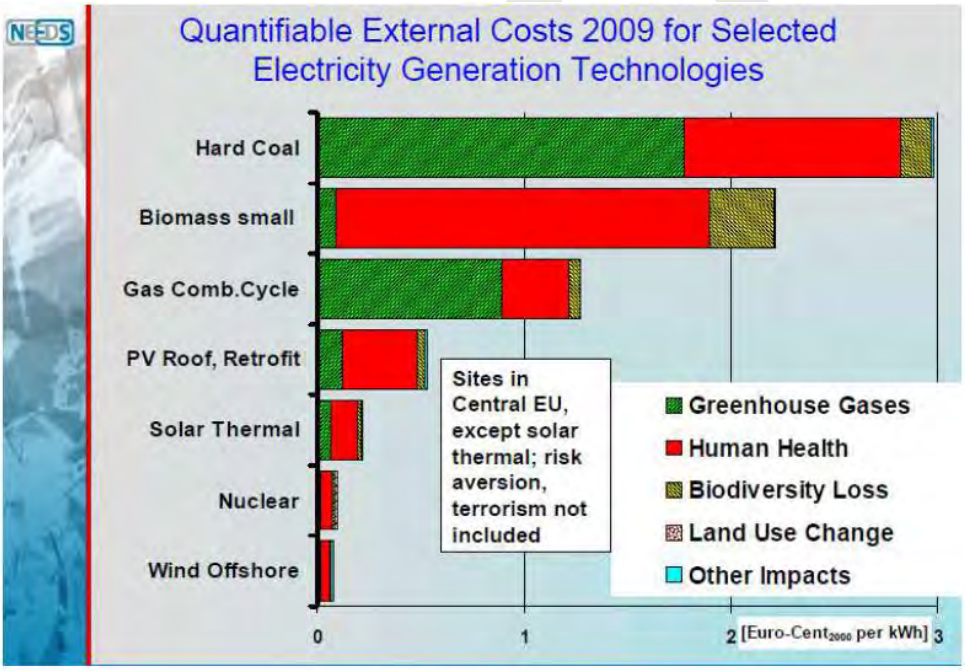
C. Giving a value to externalities is a controversial approach

The calculation of a "shadow price" to reflect the true level of damage caused by each externality has many components that are subject to debate, such as the assessment of the expense a community is willing to assume to avoid a death or the choice of an appropriate value of discount rate. (CEDD, 2013)

Furthermore, putting a price on an externality suggests that the related impact is linear: if a plant emits 50 tons of CO2, the total damage is supposed to be 50 times the damage of one ton. However there is a consensus among scientific community on the concept of "environmental thresholds", which is strongly incompatible with a linear way of thinking. (« Assessing "Societal Costs" in Order to Choose the Economic Models of Tomorrow », s. d.)

Despite these caveats, some projects have tried to give a value on electric system externalities, such as European Commission's CASES project, ExternE project and NEED project (see annex XX). We can easily see that CO2 and other GHG (climate change) and air pollutant (human health) are the two main externalities.

Annex: Here is the type of result that can be obtained



Source : Needs, R.Friedrich, 2009

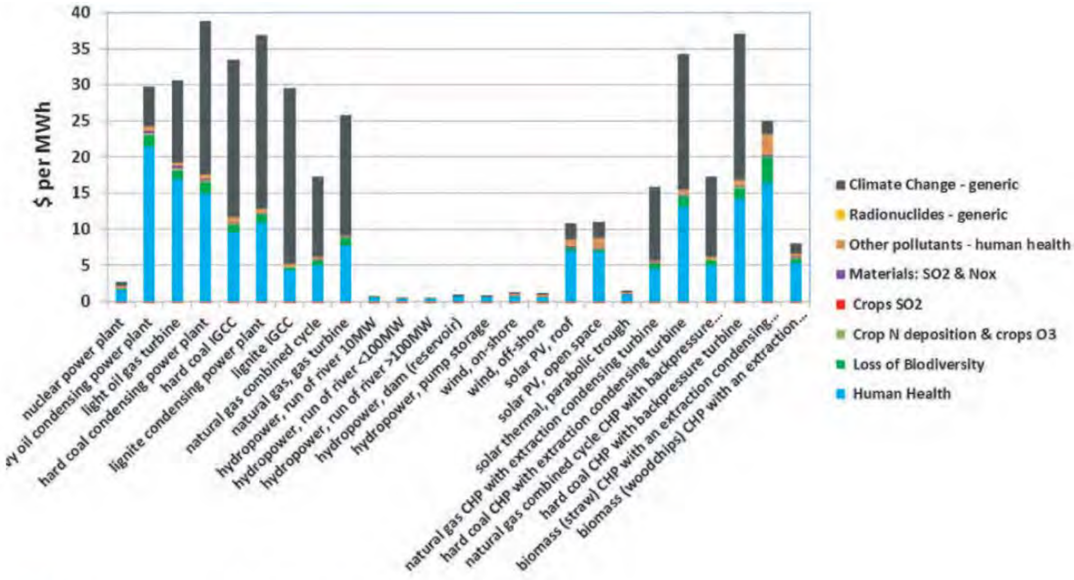


Figure 6.7 | Average external costs for the European Union. Source: Markandya et al., 2010.

Recommendations for scenario producers

The study strategy concerning externalities should be explained.

Given the controversy around putting of price on externalities, we recommend to express externalities in physical quantities in a dashboard rather than in euros within the power system inventory (see corresponding part).

However if the scenario producer prefers to translate these externalities in terms of costs, only shadow price should be used. Externality and internalized part of externality should not be mingled: for example using the price observed in the EU ETS market to internalize impact from CO2 emissions would be a significant limitation since the damage associated with CO2 emissions on society would be greatly underestimated.

D. Macroeconomic evaluation of an internalized externality: recycling of the collected money should be taken into account

Introducing an internalized externality such as a carbon pricing mechanism in a scenario can have several direct macroeconomic impacts such as a decrease of purchasing power for households. Some studies try to evaluate the macroeconomic impacts of such internalized externalities. But the use of revenues from such mechanism is sometimes forgotten in the evaluation. So as to assess the net effect, this amount of money – often paid to the State - cannot be neglected: this extra money can be recycled in several ways so as to balance the negative direct effect. (ANCRE, 2013)

Recommendations for scenario producers

When trying to evaluate the macroeconomic impact of an internalized externality such as a carbon pricing mechanism (e.g. carbon tax), the use of the revenues from this mechanism should be taken into account.

E. Internalized externality: a money transfer from system perspective but a real cost from specific **actors' perspective**

From a specific actors' perspective, internalized externalities are the costs actually paid by the actors of the electricity system or final consumers to the State for some of their externalities. From a system perspective it is only a money transfer, but when one thinks from an actor's point of view it becomes a real cost. In Europe, for example, the players in the electricity system actually pay the tons of CO_2 emitted at the price of the EU ETS market[13] which can represent a significant part of their OPEX.

Recommendations for scenario producers

When assessing costs from a specific actors' perspective, internalized externalities should be accounted.

A description of internalization implementation should be performed:

- What is the mode of internalization? *Regulation, tax, market?*
- If it is a tax or a market what is the price? If it is a regulation what is the quantity?
- If it is a tax or a market, how are the revenues reused?

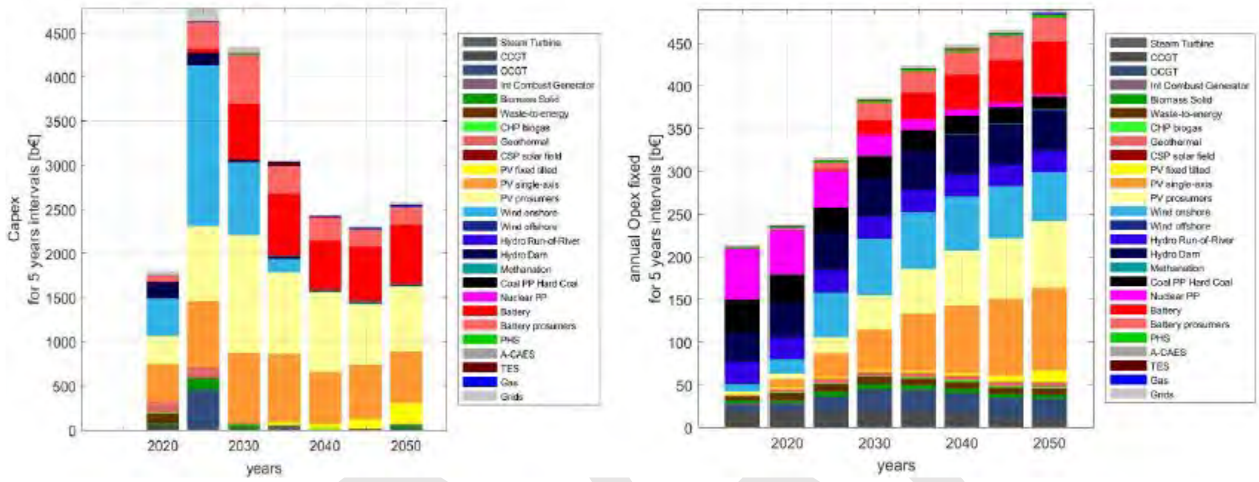
[13] This price has fluctuated between 0 and 35 €/tCO_2 approximately since EU ETS creation.

VI. Annexes

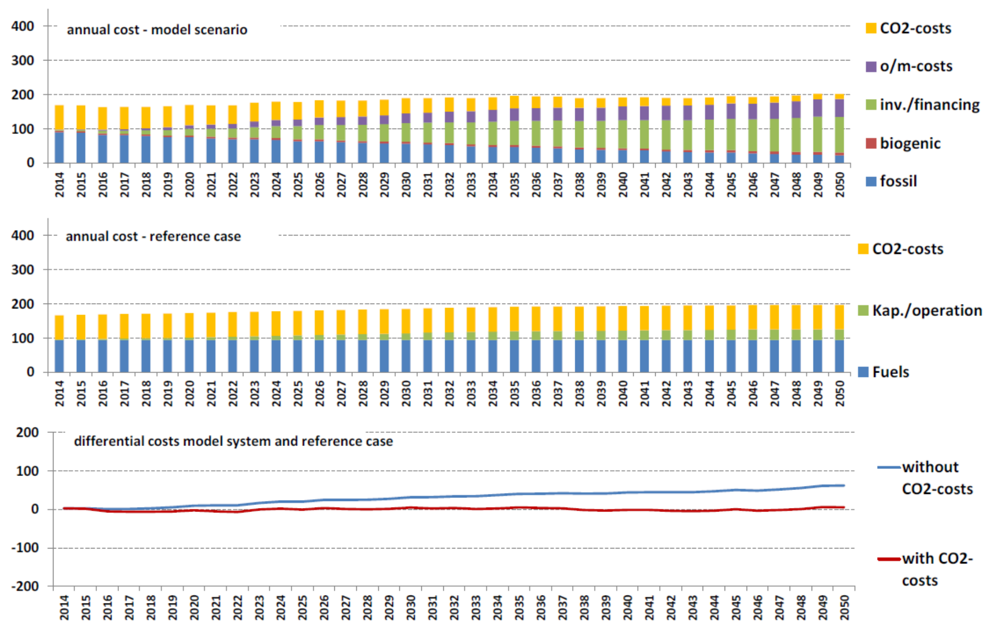
Some examples of cost trajectories indicators

The following figures are two cost trajectories from (Lappeenranta University of Technology / Energy Watch Group, 2017). They respectively show the evolution of CAPEX and OPEX of one scenario during the whole timeframe with a five year interval:

Figure 41: Global - Capital investments required in power generation and storage technologies for every 5-year interval from 2020 to 2050 (left) and annual operational expenditure required in power generation and storage technologies for every 5-year interval from 2015 to 2050 (right).



These three figures are cost trajectories from (Fraunhofer ISE, 2015). The first two show the respective cost evolution of two different scenarios, while the third one shows the differential evolution between the two scenarios:



Analysis of the 85-% Scenario

Fig. 40 The chronological cost development for the 85-% scenario (top), the fuel costs as well as CO_2 costs for the reference scenario (center), and the difference costs between model system and reference (bottom) are shown. The chart applies for constant costs of €100 per ton charged for CO_2 emissions.

Bibliography

ADEME. (2015). *Un mix électrique 100% renouvelable ? Analyses et optimisations*.

ADEME / Artelys. (2018). *Trajectoires d'évolution du mix électrique 2020-2060 - Synthèse*.

Agora Energiewende. (2015). *The Integration Costs of Wind and Solar Power*.

ANCRE. (2013). *Scénarios de l'ANCRE pour la transition énergétique*.

Assessing "Societal Costs" in Order to Choose the Economic Models of Tomorrow. (s. d.). Consulté 16 octobre 2018, à l'adresse https://lebasic.com/en/assessing-societal-cost/

Association négaWatt. (2017). *Scénario négaWatt 2017-2050 | Dossier de synthèse* (p. 48).

Belke, A., Dobnik, F., & Dreger, C. (2011). Energy consumption and economic growth: New insights into the cointegration relationship. *Energy Economics*, *33*(5), 782-789. https://doi.org/10.1016/j.eneco.2011.02.005

Brown, T. W., Bischof-Niemz, T., Blok, K., Breyer, C., Lund, H., & Mathiesen, B. V. (2018). Response to « Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems ». *Renewable and Sustainable Energy Reviews*, *92*, 834-847. https://doi.org/10.1016/j.rser.2018.04.113

Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria. (2012). *Global Energy Assessment - Toward a Sustainable Future*.

Capros, P. (s. d.). *Primes Energy System Model*. E3M Lab - National Technical University of Athens.

CEDD. (2013). *L'évaluation économique des scénarios énergétiques*.

Costs methodology for 2050 Calculator. (s. d.). Consulté 28 septembre 2018, à l'adresse http://2050-calculator-tool-wiki.decc.gov.uk/pages/28

De Clerck, Q., van Lier, T., Messagie, M., Macharis, C., Van Mierlo, J., & Vanhaverbeke, L. (2018). Total Cost for Society: A persona-based analysis of electric and conventional vehicles. *Transportation Research Part D: Transport and Environment*, *64*, 90-110. https://doi.org/10.1016/j.trd.2018.02.017

ECF. (2010). *Roadmap 2050 - A Practical Guide to a Posperous, Low-Carbon Europe*.

European Commission. (2011). *Energy Roadmap 2050 - Impact assessment and scenario analysis*.

European Commission. (2016). *EU reference scenario 2016: energy, transport and GHG emissions : trends to 2050.* Luxembourg.

Fraunhofer ISE. (2015). *What will the energy transformation cost? - Pathways for transforming the German energy system by 2050*.

Giraud, G., & Kahraman, Z. (2014). *How Dependent is Growth from Primary Energy? Output Energy Elasticity in 50 Countries*. 21.

Greenpeace. (2015). *Energy [R]evolution - A sustainable world energy outlook 2015* (p. 364).

Guivarch, C. (2011). *Évaluer le coût des politiques climatiques: de l'importance des mécanismes de second rang*. Paris-Est.

IRENA. (2018). *Global Energy Transformation: A Roadmap to 2050* (p. 76).

Jancovici, J.-M., & Grandjean, A. (2009). *C'est maintenant ! 3 ans pour sauver le monde*. Seuil.

Lappeenranta University of Technology / Energy Watch Group. (2017). *Global energy system based on 100% renewable energy - Power sector*.

OECD. (2012). *Nuclear energy and renewables: system effects in low-carbon electricity systems*. Paris.

Percebois, J. (s. d.). *Rapport Energies 2050*. 392.

RTE. (2017). *Bilan prévisionnel de l'équilibre offre-demande d'électricité en France*.

Wang, B. C., Nguyen, H., Furnback, W., Guzauskas, G. F., Hurd, J., & Garrison, L. P. (2016). PDB26 - ESTIMATING THE COST TO SOCIETY FOR EXENATIDE QW AND INSULIN GLARGINE IN THE UNITED STATES FOR THE TREATMENT OF TYPE 2 DIABETES. *Value in Health*, *19*(3), A201. https://doi.org/10.1016/j.jval.2016.03.1288

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The Shift Project

The Shift Project, a non-profit organization, is a French think-tank dedicated to informing and influencing the debate on energy transition in Europe. The Shift Project is supported by European companies that want to make the energy transition their strategic priority & by French public funding.

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Note technique : LCOE

Fiche technique – Pour discussion. Version française.

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Clés de lecture

Encart explicatif, contenant des informations clés permettant une meilleure compréhension globale du sujet.

Recommandations pour les producteurs de scénarios :

Ces cadres contiennent des recommandations pour les producteurs de scénarios.

Le terme "devrait" (ou "devraient") signifie que les producteurs de scénarios, s'ils veulent suivre les lignes directrices, doivent justifier le point correspondant. Les termes "peut" ou "pourrait" indiquent des suggestions, des idées pour aider le producteur du scénario à répondre à ce point.

Les questions en italique sont des exemples de questions que les producteurs pourraient se poser pour étayer leurs arguments. Elles sont ici dans un but d'illustration.

Les phrases surlignées en jaune font référence à d'autres documents techniques de cette série.

Introduction

Le LCOE (pour 'Levelized Cost of Energy/Electricity') est un indicateur utilisé dans de nombreuses études scénaristiques et également dans le débat public sur les questions d'énergie. Toutefois, il est tout à fait possible à la fois de construire un scénario et d'en évaluer un sans utiliser l'indicateur LCOE. C'est le cas également de nombreuses études.

Dans cette section, nous explorons donc cet indicateur à travers deux parties.

Dans un premier temps nous expliquons à quoi correspondant l'indicateur général de LCOE, sa définition et sa formule ainsi que ses limites. Puis nous distinguons et explorons deux grandes catégories de LCOE, aux usages différents, habituellement confondues derrière le terme unique de 'LCOE' : le i-LCOE et le s-LCOE. Le premier s'applique à une technologie en particulier et permet principalement de simuler des décisions d'investissement lors de la construction du mix électrique scénarisé, tandis que le second s'applique à un système et s'utilise en phase d'évaluation pour comparer des systèmes d'offre d'électricité de plusieurs scénarios.

Recommandations pour les producteurs de scénarios :

La stratégie d'un scénario vis-à-vis du LCOE devrait être définie et justifiée, au regard de la question de planification et de la stratégie globale de l'étude.

Est-ce que des indicateurs de type LCOE sont utilisés ? Pourquoi ? Si oui, quelles en sont ses utilisations ? Est-ce pour simuler des décisions d'investissement lors de la construction du mix électrique scénarisé ? Ou plutôt en phase d'évaluation pour comparer des systèmes d'offres de plusieurs scénarios ? Quelles sont les valeurs utilisées et comment sont-elles déterminées ?

I. Le LCOE, un indicateur de coût de l'électricité du côté offre du système

L'objet de cette première partie est de poser le cadre sur ce qu'est **l'indicateur LCOE de façon générale**.

Bien que cet indicateur s'applique à tout type d'énergie, il est utilisé majoritairement pour l'électricité. Nous nous focaliserons donc sur le Levelized Cost of Electricity.

De plus, cet indicateur cache en réalité deux indicateurs distincts : le premier est relatif à une filière en particulier tandis que le second est relatif à un système dans son ensemble. Ces deux usages différents sont explicités dans la partie 2.

Cette première partie traite donc des fondements communs aux deux indicateurs de type LCOE.

A. Définition du LCOE

1. Un coût de l'électricité pour une année donnée et sur un périmètre donné

Le LCOE, pour Levelized Cost of Electricity, parfois appelé « coût complet » en français, est une valeur représentant un **coût par unité d'**électricité pour une année donnée. C'est donc une façon de quantifier, à une année n, le coût de l'électricité, exprimé en €/MWh. Il s'applique en réalité à l'énergie dans son ensemble, mais nous nous focalisons ici sur le cas de l'électricité car c'est son usage majoritaire. Le LCOE peut être relatif à une technologie en particulier ou bien à un système dans son ensemble.

Le périmètre considéré peut varier. En effet, on peut prendre en compte une ou plusieurs composantes de l'inventaire du système électrique (voir Power system inventory dans le dossier Economic Evaluation). Par exemple, si on considère uniquement la composante de production, alors les coûts considérés sont ceux relatifs à cette composante uniquement, et l'électricité considérée est la quantité d'électricité produite. Le LCOE correspondant désigne alors le coût de l'électricité *produite*. Mais si on étend le périmètre à d'autres composantes, alors le LCOE peut de la même manière indiquer le coût de l'électricité *produite et transportée*, ou bien le coût de l'électricité *produite, stockée, transportée et distribuée*, etc.

De plus, certains éléments au sein de chaque composante de l'inventaire du système électrique peuvent être inclus ou non dans le périmètre. Par exemple, (ADEME / Artelys, 2018) précise que les LCOE utilisés dans leur étude intègrent les coûts de raccordement et de renforcements nécessaires sur le réseau de répartition, ce qui n'est pas toujours le cas. De la même manière, (European Commission, 2011) précise que le LCOE utilisé ne prend pas en compte de prix du CO_2, et que la composante de transport de l'électricité est prise en compte mais n'intègre pas les coûts nécessaire à certaines marges permettant d'assurer la résilience du système comme la règle du « N-k » (voir le dossier Power system operation).

Recommandations pour les producteurs de scénarios :

Lorsqu'un indicateur de type LCOE est utilisé, le périmètre relatif aux coûts et à l'énergie correspondante qui est considéré devrait être explicité. Il peut être également intéressant de justifier ce choix.

Quelles composantes de l'inventaire du système électrique sont prises en compte ? La production uniquement, la production, le stockage et le transport ?

Pour chaque composante, quels éléments sont inclus ? Est-ce que les coûts de raccordement sont considérés ? Certaines externalités ?

2. Limitation : le LCOE ne peut pas éclairer au-delà du côté offre du système

Le LCOE s'applique donc à un **système d'approvisionnement en électricité** composé d'une ou plusieurs composantes d'un système d'offre d'électricité complet. Ce système d'approvisionnement nécessite en entrée des coûts pour son fonctionnement (€) et fournit en sortie une certaine quantité d'électricité (MWh), comme illustré dans le schéma suivant :

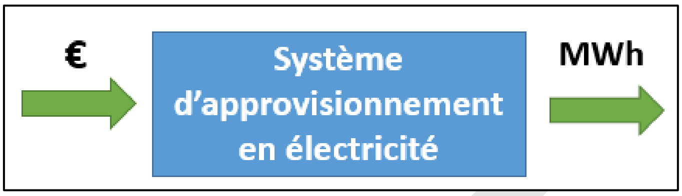

Figure 1 : L'indicateur LCOE est relatif à un système d'approvisionnement dont le périmètre est à définir

Toutefois, au maximum, ce périmètre considéré s'arrête à la porte des consommateurs finals. Ainsi, dans tous les cas, le LCOE permet de fournir des informations utiles **du côté de l'offre d'**électricité uniquement. Il ne permet pas d'éclairer la partie demande du système.

Les autres limitations relatives au LCOE dépendent de l'usage qui en est fait, et donc du type de LCOE. Elles sont donc explicitées en partie 2.

B. Formule du LCOE : division des coûts actualisés sur un périmètre **donné par l'**électricité correspondante

Le LCOE se calcule simplement **en divisant l'ensemble des coûts associés au périmètre considéré,** sur la durée de vie totale de l'installation en question, **par la quantité totale d'**électricité correspondante (c'est-à-dire la quantité d'électricité sortant du système d'approvisionnement défini). Le tout doit être actualisé pour tenir compte du fait que le flux d'argent dépensé et le flux d'électricité produite (et éventuellement stockée, transportée, etc.) s'étalent dans le futur. Pour un raisonnement détaillé sur cette étape, voir la fiche Discount Rate.

La formule générale est donc :

$$\text{LCOE} = \frac{\text{Somme actualisée du total des CAPEX \& OPEX}}{\text{Somme actualisée de l'électricité correspondante}}$$

On retrouve les coûts d'investissement et d'opération et maintenance au numérateur, et l'électricité correspondante au dénominateur, qui dépendent du périmètre choisi. Procéder à une somme actualisée nécessite de choisir une valeur de taux d'actualisation. Ce choix est discuté dans la partie 2.

NB : Dans le cas où l'ensemble des investissements ont lieu la première année, leur actualisation est inutile puisque ces coûts ne s'étalent pas le temps (elle n'a aucun effet : *Somme actualisée des CAPEX = CAPEX*). C'est pour cette raison que l'on rencontre parfois la formule suivante :

$$\text{LCOE} = \frac{\text{CAPEX + Somme actualisée du total des OPEX}}{\text{Somme actualisée de l'électricité correspondante}}$$

C. Evolution du LCOE dans le temps **: facteurs d'évolution et construction d'une trajectoire**

Le LCOE est une valeur unique, fixe. C'est le coût de l'électricité sur un périmètre donnée et pour une année donnée. En effet, bien que les coûts et l'électricité correspondante s'étalent en réalité dans le futur, l'actualisation permet de « ramener » les calculs depuis le prisme de l'année n choisie.

Or, de nombreux facteurs qui évoluent dans le temps peuvent **faire évoluer un LCOE d'une année sur l'autre**, pour une même filière ou un même système. En voici quelques exemples (non exhaustif) :

- Au niveau des coûts, les progrès techniques peuvent faire diminuer certains coûts d'investissement ou de maintenance, les prix des combustibles et des matières premières peuvent évoluer, ainsi que celui des externalités internalisées (comme le CO2 sous le mécanisme d'EU ETS). La régulation et les éventuels mécanismes de subvention peuvent eux aussi évoluer au cours du temps.

- **Au niveau de l'**électricité correspondante, les progrès techniques peuvent permettre d'allonger la durée de vie ou améliorer les rendements de certaines installations, que ce soit pour des infrastructures de production, transport, stockage d'électricité, etc. Egalement, certaines installations peuvent être affectées au niveau de la ressource dont elles dépendent ou de leur capacité de fonctionnement du fait de facteurs tels que les impacts du changement climatique : la production hydroélectrique et la capacité de refroidissement des centrales nucléaires affectées par la baisse de ressource en eau, les câbles du réseau électrique et les rendements des panneaux PV affectés par des températures plus élevées, etc. Pour plus de détails, voir les paragraphes climate change impact on power generation / on grid dans la fiche Supply-side of the power system.

- **Au niveau du taux d'actualisation**, celui-ci peut typiquement diminuer à mesure que la maturité technologique d'une filière augmente, comme cela est expliqué dans la fiche Discount rate.

Ainsi, afin d'obtenir l'évolution d'un LCOE au cours du temps, il faut calculer la valeur du LCOE à un pas de temps régulier, par exemple chaque année, en intégrant l'évolution de ces différents facteurs. Pour ce faire, pour chaque année n, on calcule le LCOE correspondant en prenant les valeurs de CAPEX, OPEX, et d'électricité correspondante que l'on projette être en vigueur sur l'ensemble de la durée de vie de l'installation ou du système mis en service à l'année n. À chaque année n, le LCOE est donc bien calculé « depuis le prisme de l'année n ». On peut construire ainsi progressivement la trajectoire d'évolution d'un LCOE sur l'ensemble de la durée d'un scénario.

NB : comprendre ce mécanisme de construction permet d'éviter les raisonnements erronés du type « Il est normal que le LCOE diminue au cours du temps puisqu'il y a une actualisation dans le calcul ».

Recommandations pour les producteurs de scénarios :

La dynamique d'évolution des indicateurs de LCOE utilisés devrait être explicitée et illustrée par un narratif sur l'évolution des facteurs influençant leurs valeurs.

Est-ce que le LCOE de cette installation / ce système diminue au cours du temps ? Comment l'évolution des progrès techniques dans le scénario en question influencent cette valeur au cours du temps ? Et celle du prix des combustibles fossiles et des matières premières, des mécanismes de soutien, du changement climatique, … ?

II. Deux types : i-LCOE et s-LCOE

Deux types de LCOE pour deux usages différents

i-LCOE - « LCOE investisseurs »

C'est en général l'indicateur auquel on pense lorsqu'on parle de LCOE.

C'est un indicateur utile dans la prise de décision des investisseurs, qui leur permet d'estimer la rentabilité **d'un investissement**. Le i-LCOE s'applique ainsi à des projets en particuliers (une unité de production, une unité de stockage, etc.) Dans les études scénaristiques, il s'applique à une technologie en particulier et s'utilise principalement pour **simuler des décisions d'investissement** (et également pour nourrir la réflexion sur divers éléments). C'est un usage qui intervient à l'étape de construction du mix électrique scénarisé. Pour cela, il est nécessaire de prendre en compte le fait que la rémunération moyenne obtenue sur les marchés de l'électricité diffère selon les filières.

Le i-LCOE est régulièrement utilisé tel quel pour tenter de comparer plusieurs filières entre elles afin de discuter de leurs compétitivités respectives et d'en déduire ce qui est 'bon' pour le système. **C'est une** pratique au mieux inutile, au pire trompeuse.

D'abord car les rémunérations diffèrent selon les filières. Ensuite parce que le i-LCOE ne prend pas en compte un ensemble de coûts 'système', autrement appelés coûts d'intégration. De nombreuses études tentent d'estimer ces coûts d'intégration afin de les ajouter aux i-LCOE, mais ces calculs sont sujets à de nombreux débats et la prise en compte de ces coûts ne fait de toute façon pas du i-LCOE un indicateur système pour autant.

Ainsi, **il est préférable d'utiliser le i**-LCOE uniquement pour les usages auxquels il est adapté (simuler des décisions d'investissement et parfois nourrir la réflexion), et d'utiliser un autre type d'indicateur tel que le s-LCOE pour raisonner à l'échelle d'un système[1].

s-LCOE - « LCOE système »

C'est un indicateur également utilisé sous le nom de 'LCOE', mais qui est en réalité très différent. Il permet de qualifier un système et non pas une technologie, et s'utilise pour **comparer les systèmes d'offre** de plusieurs scénarios. C'est un usage qui intervient une fois que la construction du mix électrique scénarisé est terminée, en phase **d'évaluation** de scénarios. Si le périmètre des coûts considéré est assez large, alors cet indicateur permet de refléter le prix hors taxes **de l'électricité pour les consommateurs finals**. Si le périmètre est plus restreint, il peut être vu comme une fraction de ce prix. Le s-LCOE se construit comme un agrégat partant des i-LCOE des différents éléments du système considéré. Un grand avantage du s-LCOE par rapport aux i-LCOE est qu'il n'y a pas **besoin d'attribuer les coûts à des technologies en particulier**[1].

En revanche, quel que soit le périmètre du s-LCOE, celui-ci permet au maximum d'évaluer l'ensemble du système d'offre d'électricité. Ainsi, cet indicateur **ne permet pas de s'intéresser à la demande**. Le s-LCOE permet d'éclairer le point de vue 'système' ainsi que celui des consommateurs finals dans le cas où la consommation des scénarios en question est fixée.

En résumé, le s-LCOE permet d'apporter des éléments de réponse à la question suivante : « En raisonnant avec un même niveau de demande entre deux scénarios, lequel présente un système d'offre (entier ou seulement une fraction) permettant d'y répondre à 'moindre coût' ? »

Pour mener une évaluation économique de scénario à la fois du côté offre et du côté demande, depuis un point de vue système, il existe d'autres indicateurs. C'est l'objet de la section Economic Evaluation.

[1] Notamment les coûts dits « système », c'est-à-dire ceux difficilement attribuables à une technologie en particulier.

En résumé :

	Objet	Etape	Usage principal dans les scénarios	Point de vue
i-LCOE	Une technologie	Construction du mix électrique scénarisé	Simuler des décisions d'investissement	Investisseurs
s-LCOE	Un système	Evaluation du mix électrique scénarisé	Comparer les systèmes d'offre de plusieurs scénarios	Système / consommateurs finals

Figure 2 : Tableau récapitulatif de l'usage des différents types de LCOE dans les études scénaristiques

A. Le i-LCOE, ou LCOE **"investisseurs"** : simuler des décisions **d'investissement pour construire une trajectoire**

Le premier type de LCOE est celui que nous avons appelé « i-LCOE », pour « LCOE investisseurs ». C'est le type le plus utilisé, auquel on pense en premier quand on parle de LCOE.

1. Un indicateur relatif à une filière en particulier

Il s'applique dans les scénarios à une filière en particulier. Le i-LCOE permet donc d'indiquer, pour une année donnée, le coût de l'électricité pour cette filière.

Le plus souvent, ce sont des filières de production d'électricité. Dans ce cas, le i-LCOE indique donc *le coût de l'électricité produite* pour cette technologie en particulier. Il peut également s'appliquer à d'autres types de filières, comme des technologies de stockage d'électricité. Dans ce cas le périmètre choisi est différent, et le i-LCOE correspondant indique alors *le coût de l'électricité stockée* (puis déstockée), comme dans l'étude (ADEME, 2015) par exemple.

NB : Initialement, le i-LCOE est un indicateur qui s'applique à chaque projet. En effet, deux projets différents utilisant la même technologie n'ont pas nécessairement les mêmes caractéristiques et présentent donc des i-LCOE différents. Ainsi, le i-LCOE par filière est une sorte d'agrégat de l'ensemble des i-LCOE des différents projets de cette filière.

2. Le i-LCOE est construit pour éclairer le point de vue des investisseurs

L'utilité première de cet indicateur dans le monde réel est d'estimer la rentabilité d'un projet dans une optique de décision d'investissement.

En effet, le i-LCOE reflète le coût de l'électricité d'une installation en particulier, en incluant l'attente de rémunération des financeurs. Il suffit donc de comparer sa valeur à la rémunération que l'on peut espérer sur les marchés pour avoir une première idée de la rentabilité du projet.

Ainsi, le i-LCOE permet d'apporter une première réponse à la question « Est-ce que ce projet est un investissement rentable pour mon activité ? ». C'est donc un indicateur permettant d'éclairer le point de **vue d'acteurs privés**, d'où son appellation « LCOE investisseurs ».

Le prix moyen espéré sur les marchés dits « de gros » (wholesale market) ne doit pas être confondu avec le prix payé par les ménages (retail price), qui est composé à la fois du prix de gros, d'une rémunération des gestionnaires des réseaux de transport et de distribution, ainsi que de taxes.

3. Calcul du i-LCOE : un WACC pour taux d'actualisation et de nombreux paramètres clés

Le i-LCOE se calcule avec la formule présentée en partie 1.

a. Illustration avec une unité de production d'électricité

Pour donner une illustration, voici la décomposition des variables qui entrent en compte dans le calcul du i-LCOE **d'une unité de production d'électricité** :

- Les coûts

- Coûts d'investissement (CAPEX)
- Coûts d'opération et maintenance (OPEX). C'est la somme des coûts de maintenance, du coût du combustible (charbon, gas, uranium, …), du coût des externalités comme le CO2, et éventuellement d'autres dépenses comme le coût de raccordement.

- **L'**électricité produite. Celle-ci calculée à partir des caractéristiques de la centrale : sa durée de vie, sa puissance et son facteur de charge.

- **Le taux d'actualisation**

NB : les coûts sont parfois comptés relativement à une unité de puissance installée, en €/kW. Dans ce cas, la puissance est déjà prise en compte et n'apparait plus au dénominateur de la formule.

b. Choix du taux d'actualisation : un WACC pour intégrer l'attente de rémunération des financeurs

Pour le choix du taux d'actualisation, puisque le i-LCOE est un indicateur utile depuis le point de vue des investisseurs, il est nécessaire de faire apparaitre un coût du capital (attente de rémunération des financeurs). Autrement, le i-LCOE obtenu ne pourrait pas être comparé au prix de marché de l'électricité afin d'estimer si l'investissement en question a des chances d'être rentable.

Pour cela, le taux d'actualisation choisi doit être un taux d'actualisation privé, autrement appelé un WACC. Ainsi, (RTE, 2017) par exemple décrit explicitement ses choix de WACC, qui diffèrent - parfois de façon importante - d'une filière à l'autre, en intégrant parfois la possibilité d'une réduction de la valeur du WACC dans le cas d'une intervention publique. Dans d'autres études, le WACC est le même pour toutes les filières, ce qui est évidemment une simplification de la réalité puisque cela occulte certaines différences entre les filières. Pour plus de détails, voir la section sur le Taux d'actualisation.

Le WACC est un paramètre très sensible, qui peut faire grandement varier la valeur d'un i-LCOE. Pour en donner une idée, il n'est par exemple pas étonnant pour certaines filières de voir la valeur d'un i-LCOE doubler lorsque le WACC passe de 0% à 8% (ce qui signifie dans ce cas qu'avec un WACC à 8%, la moitié des coûts est due à l'attente de rémunération des financeurs).

Recommandations pour les producteurs de scénarios :

Le choix des WACC utilisés dans le calcul des i-LCOE des différentes filières devrait être explicité et justifié.

Est-ce que toutes les filières ont le même WACC ou sont-ils différents ? Pourquoi ?

Puisque le choix du WACC est parfois dimensionnant, il peut être intéressant de présenter des analyses de sensibilité sur ce paramètre. D'autres recommandations sur le taux d'actualisation d'acteurs spécifiques sont présentées dans la fiche Taux d'actualisation.

c. Paramètres clés faisant varier le i-LCOE d'une filière à l'autre et d'un projet à l'autre

Les principaux facteurs d'évolution dans le temps de l'indicateur général de LCOE sont présentés en partie 1. Voici en complément des paramètres clés qui justifient, pour une année donnée, l'écart des valeurs de i-LCOE d'une filière à l'autre voire d'un projet à l'autre :

- Au niveau des coûts, chaque type d'installation est plus ou moins capitalistique (niveau de CAPEX par unité de puissance), et a des OPEX qui peuvent fortement varier notamment en fonction de la consommation de combustible et des rejets d'externalités auxquelles un prix est affecté. Tous ces coûts peuvent aussi varier en fonction du pays dans lequel le projet est installé, en fonction du coût de la main d'œuvre, de la régulation et des mécanismes de subvention en vigueur, etc.

- Au niveau **de l'**électricité correspondante, les caractéristiques techniques varient d'une filière à l'autre, mais certaines varient aussi pour une même technologie en fonction de la capacité installée (effet d'échelle) et du lieu de l'installation (meilleure ressource et donc meilleur facteur de charge typiquement).

- **Au niveau du taux d'actualisation**, celui-ci varie en fonction du risque que les investisseurs associent à chaque filière. Sa valeur est donc fortement liée à la maturité technologique de la filière. De plus, d'un projet à l'autre, la structure de financement et le pays dans lequel le projet est installé peuvent changer, ce qui influe aussi sur la valeur du taux d'actualisation.

Recommandations pour les producteurs de scénarios :

Les choix des grandeurs relatifs aux coûts et à l'électricité correspondante utilisés dans le calcul des i-LCOE des différentes filières devraient être explicités et justifiés.

Quels sont les principaux facteurs explicatifs des différences de coûts entre les filières ? Quelles sont les hypothèses sous-jacentes justifiant les valeurs des caractéristiques techniques, comme le facteur de charge par exemple ?

4. Le i-LCOE **s'utilise** lors de la construction du mix électrique scénarisé, principalement pour simuler des décisions **d'investissement**

Dans les études scénaristiques le i-LCOE s'applique à des filières plutôt qu'à des projets individuels pour des raisons évidentes de complexité, mais la logique est la même.

Son usage principal dans les scénarios est de simuler une p**rise de décision d'acteurs privés**, basée sur une comparaison avec la rémunération espérée sur les marchés.

Il est également utilisé pour nourrir des réflexions, par exemple observant l'évolution dans le temps des i-LCOE de différentes filières ou à travers des analyses de sensibilité.

On comprend donc que le i-LCOE a des usages précis, très utiles aux scénarios, mais la comparaison entre des i-LCOE **n'est en aucun cas** suffisante **pour déterminer ce qui est optimal au niveau d'un système**. Le i-LCOE ne doit pas être utilisé au-delà de son usage. Evaluer des systèmes est un usage différent, ce qui implique l'utilisation d'indicateurs différents, comme le s-LCOE par exemple.

> Recommandations pour les producteurs de scénarios :
>
> La stratégie d'utilisation du i-LCOE devrait être explicitée. Cet indicateur est approprié pour des usages tels que la simulation de prises de décisions d'acteurs privés ou simplement pour nourrir la réflexion, mais ne devrait pas être utilisé pour déterminer ce qui est optimal au niveau d'un système.
>
> *Est-ce que des i-LCOE sont utilisés ? Si oui, est-ce pour simuler des décisions d'investissement afin de construire des trajectoires ? Ou simplement pour nourrir la réflexion ?*

a. Simuler des décisions d'investissements d'acteurs privés, afin de construire une trajectoire d'évolution du mix

Son usage principal est donc de **simuler des décisions d'investissements d'acteurs privés,** afin de faire émerger une trajectoire d'évolution du mix électrique. C'est un usage qui intervient lors de la construction du mix électrique scénarisé. C'est le cas par exemple dans les études (RTE, 2017) et (ADEME / Artelys, 2018). D'autres études n'utilisent pas de i-LCOE pour construire leurs trajectoires. Ce choix dépend principalement du modèle utilisé.

Comme on l'a vu, ces décisions d'investissement se prennent en effectuant une comparaison des i-LCOE avec la rémunération espérée sur les marchés, en intégrant l'attente de rémunération des financeurs, et pour chaque technologie en particulier dans le cas des scénarios.

Toutefois, il est nécessaire de faire attention au point suivant : selon la filière, le profil de production et donc **la rémunération moyenne obtenue sur les marchés de l'électricité diffère**, car le prix varie selon l'heure de la journée. Par exemple, le prix de vente d'électricité issue d'EnR est plus faible en moyenne car elle est produite à tout moment de la journée, y compris sur les périodes creuses où le prix est plus bas (voire en majorité pendant ces périodes creuses). Et cet effet s'accentue à mesure que le taux de pénétration des EnR sur le réseau augmente.

Ainsi, pour **simuler correctement ces décisions d'investissements** lors de la construction du mix électrique scénarisé, il est nécessaire de mener une analyse « sur tous les pas de temps en intégrant les revenus perçus par chaque installation » (RTE, 2017). C'est pour cette raison que le i-LCOE en lui-même n'est pas un outil adapté pour comparer la compétitivité relative de différentes filières entre elles.

> Recommandations pour les producteurs de scénarios :
>
> Si des i-LCOE sont utilisés pour simuler des décisions d'investissements, le raisonnement derrière ces décisions devrait être explicité, afin d'expliquer concrètement comment le mix électrique se construit au cours du scénario (voir Supply-side of the power system). Pour simuler ces décisions d'investissements en accord avec la réalité, le fait que le profil de production et donc la rémunération moyenne obtenue sur les marchés diffère selon la filière devrait être intégré dans la modélisation.
>
> *Les i-LCOE sont-ils comparés à la rémunération moyenne espérée sur les marchés ? Ces rémunérations sont-elles différentes d'une filière à l'autre ? Comment cela est-il modélisé ?*

b. Nourrir la réflexion sur divers éléments

Dans de nombreuses études, le i-LCOE est également utilisé pour apporter des éléments de réflexions.

D'abord, certaines études présentent des analyses où des i-LCOE de différentes filières sont comparés à la rémunération attendue sur les marchés, mais avec pour but de nourrir la réflexion et non pas de construire des trajectoires. C'est le cas par exemple de l'étude (Agora Energiewende, 2017), qui effectue ce type d'analyse pour différentes filières d'énergies renouvelables et non renouvelables à travers des analyses de sensibilité, et en prenant évidemment en compte le fait que les rémunérations moyennes espérées diffèrent selon les filières.

Ensuite, le i-LCOE peut être également utilisé pour nourrir la réflexion sur **l'évolution du coût de l'**électricité des filières dans le temps, et donc en partie de leur compétitivité. C'est une utilisation très fréquente du i-LCOE, que l'on retrouve par exemple dans (RTE, 2017) et (OECD/IEA, 2017), qui comparent ainsi les évolutions pour les différentes filières considérées dans leurs scénarios. La baisse des coûts des EnR notamment est un thème souvent abordé par l'observation de l'évolution du i-LCOE.

Encore une fois, il faut cependant bien veiller à ne pas faire dire au i-LCOE plus que ce qu'il ne peut. Ainsi, la comparaison du i-LCOE d'une unique filière sur différentes années peut être pertinente, tout comme la comparaison des tendances d'évolution de différentes filières les unes par rapport aux autres (l'une voit son i-LCOE augmenter quand l'autre voit le sien baisser dans le temps par exemple). En revanche, la comparaison directe des valeurs de i-LCOE de filières différentes n'est pas pertinente, entre autre pour la raison mentionnée plus haut : les rémunération moyennes espérées diffèrent d'une filière à l'autre.

Enfin, de façon générale, tous les usages présentés peuvent être approfondis au moyen d'analyses de sensibilité, par exemple sur le choix de pays ou de région qui influe sur le facteur de charge, comme dans (Energy Union Choices, 2017), sur le taux d'actualisation comme dans (ADEME, 2015), ou d'autres caractéristiques spécifiques. On peut ainsi mener des analyses sur les régions du monde où les conditions sont suffisamment favorables pour l'intégration de certaines EnR selon l'ensoleillement par exemple, ou sur les seuils de prix du CO2 et des combustibles qui favorisent l'arrivée sur le marché de certaines filières, comme dans (RTE, 2017).

5. **Des coûts d'intégration** peuvent être ajoutés au i-LCOE, mais **n'en font** pas un indicateur « système » pour autant

a. Les coûts d'intégration : élargir le périmètre du i-LCOE

Le i-LCOE est souvent critiqué pour son périmètre de coûts restreint. Ainsi, de nombreuses sources appuient, de façon plus ou moins précise, le fait que de nombreux coûts ne sont pas pris en compte dans le calcul du i-LCOE, et que cela peut constituer en un biais dans certains raisonnements. En voici quelques-unes :

- (Ueckerdt, Hirth, Luderer, & Edenhofer, 2013) : "[...] there is criticism particularly towards evaluating variable renewables like wind and solar PV (photovoltaics) power based on LCOE because it ignores variability and integration costs."
- (Veyrenc, 2018) : « Le coût complet restitue le coût de l'énergie produite mais néglige le fait que les services rendus par les différentes filières sont différents. »
- (Crooks, 2019) : "In another report this week, Mark Mills, an academic and energy investor, argued that the LCOE calculations [...] were misleading, because **they failed to account for the "hidden costs"** of maintaining a stable grid with variable resources such as wind and solar."

Ainsi, de nombreuses études tentent de trouver des façons de mesurer ces « coûts cachés », ou « coûts systèmes » afin de les ajouter aux i-LCOE initiaux. C'est ce qu'on appelle les **coûts d'intégration**.

C'est le cas de (Ueckerdt et al., 2013) par exemple, ou de (Grandjean, 2017) qui distingue « coût de revient intrinsèque » (i-LCOE de base) auquel est ajouté des coût de 'back-up' et de raccordement et renforcement réseau afin de former le « coût de revient final » (i-LCOE avec coûts d'intégration).

L'AIE s'intéresse également à ce sujet. Dans la version 2011 de son World Energy Outlook, des coûts d'intégration sont évalués à travers un découpage en trois parties : les coûts de capacités de secours à prévoir, les coûts d'ajustement pour compenser les fluctuations du réseau, et les coûts de raccordement et de renforcement du réseau (Percebois, s. d.). Egalement, dans la version 2018 du WEO est introduit le « value-adjusted LCOE » (VALCOE), qui prend en compte dans son périmètre des éléments liés à la flexibilité de la fourniture d'électricité (Crooks, 2019).

b. Les coûts d'intégration restent en partie sujets à des controverses

L'étude (Agora Energiewende, 2015), « The Integration Costs of Wind and Solar Power", fait le tour de la question des coûts d'intégration. Agora Energiewende y détaille notamment différentes approches possibles pour calculer des coûts d'intégration, catégorise les éléments sur lesquels il existe un consensus et qui restent sujets à débats, et présente les biais de certains calculs et certaines approches.

Voici quelques constats importants que présente l'étude :

- Un sujet en débat. La question des coûts d'intégration est source de nombreux débats dans certains milieux académiques et de décideurs politiques.

- Une notion floue. Aucune définition consensuelle de ce que sont les coûts d'intégration n'existe, et les différents calculs sont sujets à des incertitudes importantes.

- Des éléments controversés. L'attribution de certaines composantes de coûts aux technologies entrantes sur un marché est source de controverse. C'est une question complexe qui a de grandes chances de rester longtemps en discussion.

c. Il existe toutefois des méthodologies de calcul

L'étude (Agora Energiewende, 2015) propose ensuite une approche permettant de calculer au mieux ces coûts d'intégration. Pour cela, trois composantes sont explorées :

- Les coûts réseau, pour apporter l'électricité là où il y en a besoin.

- **Les coûts d'équilibre**, afin de gérer l'écart entre la production prévue et la production réelle.

- Les coûts sur les centrales conventionnelles, appelé "utilization effect". Ce sont les coûts dus à une "interaction" avec d'autres centrales, typiquement des coûts liés à une réduction de leur facteur de charge. L'étude explique pourquoi raisonner en termes de coûts de 'back up' n'est pas une approche appropriée.

Un résumé très clair des points clés de l'étude d'Agora Energiewende est présenté dans ses premières pages, et peut être retrouvé en annexe AAA

Key Insights at a Glance

1	**Three components are typically discussed under the term "integration costs" of wind and solar energy: grid costs, balancing costs and the cost effects on conventional power plants (so-called "utilization effect").** The calculation of these costs varies tremendously depending on the specific power system and methodologies applied. Moreover, opinions diverge concerning how to attribute certain costs and benefits, not only to wind and solar energy but to the system as a whole.
2	**Integration costs for grids and balancing are well defined and rather low.** Certain costs for building electricity grids and balancing can be clearly classified without much discussion as costs that arise from the addition of new renewable energy. In the literature, these costs are often estimated at +5 to +13 EUR/MWh, even with high shares of renewables.
3	**Experts disagree on whether the "utilization effect" can (and should) be considered as integration costs, as it is difficult to quantify and new plants always modify the utilization rate of existing plants.** When new solar and wind plants are added to a power system, they reduce the utilization of the existing power plants, and thus their revenues. Thus, in most cases, the cost for "backup" power increases. Calculations of these effects range between -6 and +13 EUR/MWh in the case of Germany at a penetration of 50 percent wind and PV, depending especially on the CO_2 cost.
4	**Comparing the total system costs of different scenarios would be a more appropriate approach.** A total system cost approach can assess the cost of different wind and solar scenarios while avoiding the controversial attribution of system effects to specific technologies.

Recommandations pour les producteurs de scénarios :

Si des coûts d'intégration sont ajoutés aux i-LCOE dans le scénario, leur valeur devrait être explicitée et justifiée. En effet, il n'existe pas encore de consensus à ce sujet.

Est-ce que ces valeurs sont tirées d'une source externe ? Quelle est l'approche choisie ? Quels sont les modes de calcul ?

d. Les coûts d'intégration devraient être utilisés simplement pour apporter des éléments de réflexion

Au-delà des discussions sur les modes de calcul et des différentes approches possibles, cette démarche d'ajouter au i-LCOE des coûts d'intégration pose la question de l'usage de l'indicateur qui en résulte.

En effet, quel est le point de vue qui est éclairé ? Quelle est la question à laquelle on répond ?

Est-ce que cela permet de mieux éclairer le point de vue des investisseurs ? Non, puisque ceux-ci basent leur décisions sur le i-LCOE sans coûts d'intégration pour évaluer la rentabilité d'un projet. Ainsi, pour simuler des décisions d'investissement lors de la construction du mix électrique scénarisé, le i-LCOE est parfaitement adapté tel qu'il est.

Est-ce que cela permet alors d'évaluer des systèmes ? Non plus, car cela supposerait que l'intégralité des coûts ont été correctement pris et compte ; et surtout ce n'est pas en raisonnant par filière que l'on peut tirer les meilleures conclusions sur des systèmes. D'autres indicateurs relatifs à des systèmes, tels que le s-LCOE, sont bien plus adaptés pour cela.

Dans quel but alors la mesure de **coûts d'inté**gration peut être utilisée de façon pertinente ?

Principalement pour nourrir la réflexion. (Veyrenc, 2018) explique par exemple que cela peut constituer un outil intéressant pour comprendre les résultats issus des modèles, disposer d'ordres de grandeur et identifier les composantes dimensionnantes.

Cela peut également permettre de construire un scénario dans lequel les décisions d'investissement simulées prennent en compte ces coûts d'intégration, comme si les investisseurs devaient intégrer ces coûts « système » dans leurs arbitrages, et de voir les trajectoires qui en résultent. Cela peut constituer un moyen de simuler les effets d'un changement de réglementation par exemple.

Recommandations pour les producteurs de scénarios :

Si des coûts d'intégration sont ajoutés aux i-LCOE dans le scénario, l'usage qui est fait de l'indicateur qui en résulte devrait être explicité.

Est-ce pour mieux comprendre les résultats issus du modèle ? Est-ce pour simuler des décisions d'investissement qui intègreraient ces coûts ?

e. D'autres indicateurs doivent être préférés pour comparer des options dans une optique d'optimiser un système

On a donc vu que le i-LCOE est intéressant pour simuler le point de vue des investisseurs. Y ajouter les coûts d'intégration ne change pas la nature de cet indicateur pour autant. Comme le souligne (Agora Energiewende, 2015), le concept des coûts d'intégration essaye de répondre à la question « Comment comparer différentes technologies ? » mais peut parfois se transformer en « À qui la faute ? ». Si le but est de raisonner sur le développement long-terme du système électrique dans son ensemble, alors une meilleure question serait plutôt « Quelles sont les implications si je choisis la trajectoire A plutôt que la B ? »

C'est une idée que l'on retrouve dans d'autres études, comme dans (OECD, 2012) par exemple : "While calculations of LCOE at the plant-level remain a useful and intuitive first guide, they are an increasingly poor guide for decision-making. [There is] an increasing awareness of a need for a system approach to cost accounting also at the level of decision-and policy-makers."

Or, à usages différents des indicateurs différents. Ainsi, pour éclairer les choix au niveau du système, il suffit de choisir des indicateurs adaptés. La prochaine section présente l'un deux, le s-LCOE.

B. Le s-LCOE, ou LCOE **"système"** : comparer plusieurs systèmes **d'offre afin d'évaluer des trajectoires lorsque la demande est fixée**

Le second type de LCOE est celui que nous avons appelé « s-LCOE », pour « LCOE système ». Il est utilisé dans des études comme (Lappeenranta University of Technology / Energy Watch Group, 2017), (ECF, 2010) ou (ADEME / Artelys, 2018), sous le terme parfois de « global average energy system LCOE », parfois de « coût total », ou simplement de « LCOE ».

NB : le terme « System LCOE » peut parfois désigner un i-LCOE avec coûts d'intégration, comme dans (Ueckerdt et al., 2013) par exemple. Ce n'est pas de cet indicateur dont il s'agit ici.

1. Un indicateur relatif à un système

Le s-LCOE s'applique à un système en particulier. Il permet donc d'indiquer, pour une année donnée, le coût de **l'**électricité de ce système.

Le système évalué peut être constitué d'**une plusieurs composantes de l'in**ventaire du système électrique, **du côté de l'offre** : cela peut être l'ensemble des moyens de production d'électricité, l'ensemble de moyens de production, de transport et de stockage d'électricité, etc. Au maximum, le périmètre du s-LCOE s'arrête à la porte du consommateur, c'est-à-dire qu'il prend en compte l'ensemble du système d'offre.

L'étude (ECF, 2010) par exemple prend en compte l'ensemble des coûts de production et de transport du système. Le s-LCOE qui en résulte est donc en quelques sortes un « Levelized cost of power generation and transmission system ».

Bien évidemment, lorsque plusieurs composantes sont considérées, le s-LCOE peut se décomposer par composante. C'est ce que fait par exemple l'étude (Lappeenranta University of Technology / Energy Watch Group, 2017), qui utilise un s-LCOE prenant en compte les systèmes de production, de stockage, et de transport d'électricité.

Le s-LCOE a une valeur ajoutée immédiate par rapport aux i-LCOE : il devient **inutile d'essayer d'attribuer des** coûts à des technologies en particulier. Se placer au niveau du système permet de simplement sommer les coûts du système de production avec ceux du système de stockage sans avoir à distribuer les coûts de stockage sur des technologies de production d'électricité.

2. Le s-LCOE se calcule comme un agrégat de i-LCOE

Dans les études que nous avons regardées, il n'était pas toujours évident de savoir comment le s-LCOE était calculé, mais en toute logique celui-ci était calculé pour chaque année n donnée selon deux possibilités :

- Soit via la formule de LCOE présentée en première partie, avec l'ensemble des CAPEX et OPEX, et l'électricité correspondante. Le taux d'actualisation choisi est alors un WACC.

- Soit comme une moyenne des i-LCOE des différentes technologies considérées pondérée par leurs **quantités d'**électricité correspondante (électricité produite, stockée, etc.) Cette fois-ci pas de choix de taux d'actualisation, puisque les i-LCOE intègrent déjà des WACC.

Dans les deux cas, les composantes du système n'ayant pas de i-LCOE attribué (comme la composante de transport d'électricité par exemple) peuvent être directement ajoutée au numérateur dans le calcul (dans les coûts).

De plus, ces deux méthodes sont équivalentes si on considère que toutes les filières ont le même WACC unique et fixé.

Ainsi, quelle que soit la méthode choisie, le s-LCOE est calculé dans une logique d'**agrégat de l'**ensemble des i-LCOE des différents éléments du système considéré. Utiliser l'indicateur s-LCOE suppose donc que le système de financement est le même qu'aujourd'hui tout au long du scénario, car **l'attente de rémunération des** financeurs est incluse dans les calculs.

NB : il serait possible d'imaginer un s-LCOE calculé avec la formule LCOE et un taux d'actualisation social. Cependant nous n'avons pas vu de tel indicateur, qui serait de nature différente du s-LCOE présenté ici, et dont l'usage serait à discuter.

Recommandations pour les producteurs de scénarios :

Lorsqu'un indicateur de type s-LCOE est utilisé, il peut être intéressant de développer son mode de calcul.

Est-ce un calcul basé sur la formule de LCOE ? Dans ce cas quel est le taux d'actualisation choisi ? Ou est-ce plutôt une moyenne des différents i-LCOE pondérée par leurs quantités d'énergie correspondantes ? Dans ce cas est-ce que chaque type d'installation a un i-LCOE unique qui évolue avec le temps, ou est-ce que chaque installation garde le i-LCOE qui correspond à son année de mise en service ?

3. Le s-**LCOE s'utilise en phase d'évaluation** des scénarios pour comparer plusieurs trajectoires entre elles, mais uniquement côté offre

Le s-LCOE permet de comparer plusieurs scénarios entre eux. Cet indicateur s'utilise donc en phase **d'évaluation** d'un scénario.

a. Eclairer le point de vue 'système' en comparant tout ou partie de différents systèmes d'offre d'électricité

Plus exactement, le principal usage du s-LCOE est de comparer une ou plusieurs composantes de systèmes **d'offre d'électri**cité - **au maximum l'ensemble de ces systèmes d'offre** - de plusieurs scénarios.

C'est le cas de l'étude (ECF, 2010) par exemple, qui compare les systèmes de production et transport d'électricité de ses quatre principaux scénarios en utilisant un s-LCOE basé sur le périmètre correspondant, afin de nourrir la réflexion sur l'analyse des grands résultats pour ces quatre trajectoires. Par ailleurs, il est possible d'affiner la comparaison grâce à des analyses de sensibilité. C'est ce que fait l'étude (ECF, 2010), en étudiant les variations des s-LCOE des différents scénarios en fonction du prix du carbone, du prix des énergies fossiles, du progrès technologique ; ou à l'inverse en étudiant l'impact sur les trajectoires de PIB des différentes valeurs de s-LCOE.

D'autres indicateurs permettant d'évaluer des coûts d'un point de vue système existent, et sont présentés dans la section Economic Evaluation.

b. Eclairer le point de vue des consommateurs finals en estimant tout ou partie du prix hors taxes de l'électricité

De plus, si le s-**LCOE s'étend sur l'ensemble du système d'offre, alors il reflète le prix** hors taxes de **l'électricité pour les consommateurs finals.** En effet, le prix de l'électricité pour les consommateurs finals est composé, directement ou indirectement, de l'ensemble des coûts relatifs au système d'offre d'électricité, auquel s'ajoutent des taxes, en prenant en compte l'attente de rémunération des financeurs.

(ADEME / Artelys, 2018) par exemple présente l'évolution des s-LCOE des différentes trajectoires de l'étude, et approxime avec cet indicateur le « coût total de l'électricité facturée au consommateur, hors taxes ». Le s-LCOE peut ainsi permettre d'éclairer le point du vue 'système' et celui des consommateurs finals.

Toutefois, il faut noter que **prendre en compte l'ensemble des composantes du système d'offre d'électricité peut être un exercice compliqué** : par exemple, on peut noter que l'ensemble des études utilisant un s-LCOE que nous avons regardées ne prennent pas en compte les coûts du système de distribution (ou supposent qu'ils restent constants au cours du scénario), probablement par manque d'informations disponibles à ce sujet.

Ainsi, lorsque le périmètre du s-LCOE ne s'étend pas sur l'ensemble du système d'offre, la comparaison de sa valeur avec celle observée aujourd'hui du prix hors taxes de l'électricité pour les consommateurs finals est incorrecte.

Il est donc plus juste de considérer le s-LCOE comme **une 'fraction' du prix total l'électricité pour les** consommateurs finals hors taxes, cette 'fraction' étant celle du périmètre étudié. Cette approche reste utile pour comparer deux scénarios aux périmètres similaires.

Recommandations pour les producteurs de scénarios :

Lorsque la valeur du s-LCOE d'un scénario est comparée au prix actuel ou passé de l'électricité hors taxes pour les consommateurs finals, alors ce s-LCOE devrait être basé sur un périmètre qui prend en compte l'ensemble du système d'offre.

Si un s-LCOE est basé sur une partie seulement d'un système d'offre d'électricité, celui-ci peut alors être vu comme un prix de l'électricité *partiel* pour les consommateurs finals, relatif au périmètre considéré, et devrait être comparé à la fraction correspondante du prix actuel ou passé de l'électricité hors taxes. Si un tel s-LCOE est toutefois comparé avec un prix *complet* de l'électricité hors taxes pour les consommateurs finals, alors l'ampleur de l'écart entre les deux valeurs devrait être commentée.

c. Un indicateur limité au côté offre du système

Ainsi, le s-LCOE permet d'apporter des éléments de réponse à la question « Est-ce que cette fraction de **système d'offre est plus ou moins coûteuse dans un scénario A** par rapport à un scénario B ? », sans prendre en compte de taxes et en supposant que le système de financement reste le même qu'aujourd'hui puisque ce prix de l'électricité inclut l'attente de rémunération des financeurs. La partie du système d'offre en question est celle du périmètre du s-LCOE.

NB : pour qu'une telle comparaison soit viable, il est nécessaire que les périmètres des s-LCOE des scénarios A et B soient à la fois similaires et suffisants, comme cela est développé dans le paragraphe dédié de la section Economic Evaluation.

Toutefois, il est important de garder à l'esprit que le s-LCOE, comme tout type de LCOE, reste limité au côté offre du système (le LCOE est en effet relatif à un système d'approvisionnement comme illustré dans la partie 1). Dans tous les cas, cet indicateur ne permet donc pas de s'intéresser à la demande. Ainsi, pour évaluer des systèmes de façon pertinente à travers l'utilisation du s-LCOE, un prérequis est que les différentes trajectoires qui sont comparées présentent un même niveau de demande.

Si on précise la question à laquelle le s-LCOE permet d'apporter un élément de réponse, cela donne : « En raisonnant avec un même niveau de demande entre deux scénarios, lequel présente un système **d'offre (entier ou seulement une fraction)** permettant **d'y répondre à 'moindre coût'** ? »

Or, faire varier la demande peut être une solution particulièrement coût-efficace pour atteindre certains objectifs. L'importance de considérer le côté de la consommation est un diagnostic consensuel qui tend à émerger, notamment sur l'enjeu que représente la réduction de la consommation d'énergie. (Tissot-Colle & Jouzel, 2013)

D'autres méthodes plus complètes d'évaluation des systèmes existent. Nous en présentons une de façon détaillée dans la section Economic Evaluation.

Recommandations pour les producteurs de scénarios :

Le s-LCOE est un indicateur du côté du système d'offre d'électricité uniquement. Ainsi, cet indicateur ne devrait être utilisé pour évaluer et comparer des scénarios de façon pertinente seulement si les différents scénarios ont un même niveau de demande.

Autrement, d'autres indicateurs devraient être préférés.

III. Bibliographie

ADEME. (2015). *Un mix électrique 100% renouvelable ? Analyses et optimisations*.

ADEME / Artelys. (2018). *Trajectoires d'évolution du mix électrique 2020-2060 - Synthèse*.

Agora Energiewende. (2015). *The Integration Costs of Wind and Solar Power*.

Agora Energiewende. (2017). *Renewables versus fossil fuels – comparing the costs of electricity systems*.

Crooks, E. (2019, mars 30). *The week in energy: Predicting the power shift | Financial Times*.

ECF. (2010). *Roadmap 2050 - A Practical Guide to a Posperous, Low-Carbon Europe*.

Energy Union Choices. (2017). *Cleaner Smarter Cheaper*.

European Commission. (2011). *Energy Roadmap 2050 - Impact assessment and scenario analysis*.

Grandjean, A. (2017). *NUCLÉAIRE - Une feuille de route pour ouvrir une vraie alternative*.

Lappeenranta University of Technology / Energy Watch Group. (2017). *Global energy system based on 100% renewable energy - Power sector*.

OECD. (2012). *Nuclear energy and renewables: system effects in low-carbon electricity systems*. Paris.

OECD/IEA. (2017). *World Energy Outlook 2017* (p. 782).

Percebois, J. (s. d.). *Rapport Energies 2050*. 392.

RTE. (2017). *Bilan prévisionnel de l'équilibre offre-demande d'électricité en France*.

Tissot-Colle, C., & Jouzel, J. (2013). *La transition énergétique : 2020-2050 : un avenir à bâtir, une voie à tracer*. Consulté à l'adresse Les avis du conseil économique, social et environnemental website: https://www.lecese.fr/sites/default/files/pdf/Avis/2013/2013_02_transition_energetique.pdf

Ueckerdt, F., Hirth, L., Luderer, G., & Edenhofer, O. (2013). System LCOE: What are the costs of variable renewables? *Energy*, *63*, 61-75. https://doi.org/10.1016/j.energy.2013.10.072

Veyrenc, T. (2018). *Analyser les trajectoires EnR sous l'angle économique dans les scénarios de transition électrique*. RTE.

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Valentin Labre a rejoint le Shift pour travailler aux côtés de Nicolas Raillard sur le projet Power Systems 2050, qui vise à élaborer un référentiel méthodologique portant sur la scénarisation des systèmes électriques. Ingénieur diplômé de l'École centrale d'électronique de Paris (ECE), il a complété son parcours avec le Master 2 d'économie de l'énergie « Énergie, Finance, Carbone » à l'Université Paris-Dauphine. Il rejoint le Shift après plusieurs expériences dans l'énergie, notamment chez le gestionnaire du réseau de distribution électrique Enedis et le producteur d'énergie décentralisée GreenYellow.

The Shift Project

The Shift Project, a non-profit organization, is a French think-tank dedicated to informing and influencing the debate on energy transition in Europe. The Shift Project is supported by European companies that want to make the energy transition their strategic priority & by French public funding.

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Note technique : taux d'actualisation

Fiche technique – Pour discussion. Version française.

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Clés de lecture

Encart explicatif, contenant des informations clés permettant une meilleure compréhension globale du sujet.

Recommandations pour les producteurs de scénarios :

Ces cadres contiennent des recommandations pour les producteurs de scénarios.

Le terme "devrait" (ou "devraient") signifie que les producteurs de scénarios, s'ils veulent suivre les lignes directrices, doivent justifier le point correspondant. Les termes "peut" ou "pourrait" indiquent des suggestions, des idées pour aider le producteur du scénario à répondre à ce point.

Les questions en italique sont des exemples de questions que les producteurs pourraient se poser pour étayer leurs arguments. Elles sont ici dans un but d'illustration.

Les phrases surlignées en jaune font référence à d'autres documents techniques de cette série.

I. La valeur accordée à l'avenir

Le taux d'actualisation est une variable clé au sein d'une formule servant d'**outil d'aide à la comparaison de** différentes options qui s'expriment sous la forme de trajectoires qui **s'étalent dans le futur**. L'objectif est de comparer depuis le prisme d'aujourd'hui ces flux dynamiques en les actualisant : l'enjeu est d'assurer une cohérence intertemporelle des choix.

La formule générale permettant d'actualiser un flux est la suivante : $\frac{\sum X_i}{(1+r)^i}$;

avec i les années (de 1 à 20 ans par exemple), X une grandeur au choix dont le flux s'étend au cours des années (des coûts, des émissions de CO_2, etc.), et r le taux d'actualisation.

Dans la quasi-totalité des cas, ce taux a une valeur positive, ce qui signifie que disposer d'un euro immédiatement a plus de valeur que de n'en disposer que dans un an. Le taux d'actualisation permet de donner une valeur à cette dépréciation. C'est d'une certaine manière le prix du temps. La valeur du taux d'actualisation choisi dépend de la grandeur X en question, de l'acteur à l'origine de la comparaison ainsi que de choix subjectifs.

Nous distinguerons ici **quatre types d'acteurs** : les individus (ménages), les acteurs privés (entreprises, investisseurs, …), l'acteur public (Etat), et le « planificateur bienveillant », acteur théorique dont le but est de maximiser le bien-être social sans certaines contraintes pratiques. Un taux d'actualisation peut permettre par exemple pour un acteur de décider d'un investissement, autrement dit de déterminer le seuil au-delà duquel l'argent investi aujourd'hui pour plus tard est 'rentable' d'un point de vue d'optimum économique ou socio-économique.

C'est un paramètre très sensible, dont le calibrage peut rendre un même projet rentable ou non selon la valeur choisie. Il pourrait même avoir un impact significatif sur les trajectoires de certains scénarios. Afin d'illustrer cette sensibilité, le graphique suivant présente une situation fictive où l'on doit payer 10€ par an pendant 40 ans. On a le choix entre trois 'visions', trois choix de vitesse à laquelle on estime que ce paiement perd en importance à nos yeux à mesure qu'il s'éloigne dans le temps (c'est bien une vue de l'esprit, il faudra dans tous les cas payer 10€ chaque année). Chaque choix est représenté par une valeur de taux d'actualisation : 0%, 2%, et 7%. On obtient alors les flux suivant :

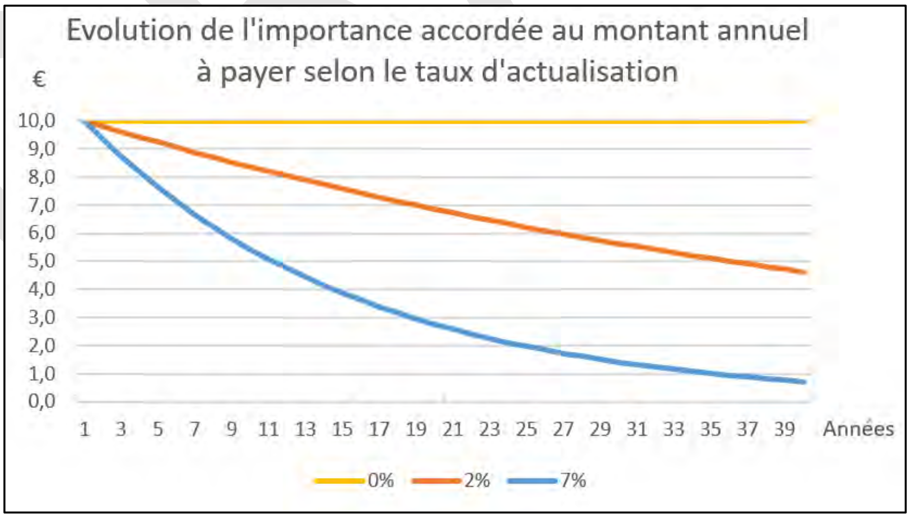

Figure 1 : Illustration de l'impact d'une actualisation sur un paiement annuel de 10€ pendant 40 ans, selon trois taux différents.

Pour un taux de 0% la valeur est constante (pas d'actualisation). Pour le taux à 7%, la valeur est divisée par deux à l'horizon de 10 ans, et descend **en dessous de 1€ passé 35 ans**. On comprend ici pourquoi les raisonnements économiques de court ou moyen terme prennent mal en compte les grands défis de long terme tels que le changement climatique : **dès 7 à 8% de taux d'actualisation, l'h**orizon 40 ans « **n'existe plus** ».

II. Usages du taux d'actualisation dans les scénarios : simuler des décisions et comparer des trajectoires

Nous distinguerons ici **deux grandes catégories d'usage** du taux d'actualisation que l'on retrouve dans les études scénaristiques : l'actualisation dans des analyses coûts-bénéfices pour la modélisation de décisions des acteurs lors de la construction du mix (d'offre et/ou de demande) d'un scénario, et le calcul a posteriori de certaines grandeurs pour évaluer un ou plusieurs scénarios et les comparer. Le premier usage implique les acteurs individuels, privés et/ou l'acteur public, tandis que le second correspond à l'approche de « planification bienveillante ».

Les deux catégories ne sont pas contradictoires, elles interviennent simplement à des moments différents du raisonnement et peuvent être utilisées de façon complémentaire.

Recommandations pour les producteurs de scénarios :

Lorsqu'on des flux dynamiques s'étalant dans le futur sont utilisés, la stratégie d'un scénario vis-à-vis de l'utilisation de taux d'actualisation devrait être définie et justifiée.

Est-ce que des taux d'actualisation sont utilisés ? Si non, pourquoi l'utilisation de taux d'actualisation n'était-elle pas utile ? Est-ce que ces flux s'étalant dans le futur ne nécessitaient pas d'être estimés depuis le prisme d'aujourd'hui ?

Si des taux d'actualisation sont utilisés, les choix d'usage et d'acteur concerné devraient être explicités et justifiés.

Est-ce que des taux d'actualisation sont utilisés pour évaluer et comparer plusieurs scénarios du point de vue de planificateur bienveillant ? Ou est-ce pour simuler des décisions d'investissement ? Dans ce cas, ces décisions sont-elles prises par des acteurs privés, des ménages, l'acteur public ?

A. Simuler des décisions d'acteurs arbitrant entre différents investissements

1. Choix d'investissements privés : un taux d'actualisation privé pour intégrer l'attente de rémunération des financeurs

Le taux d'actualisation privé est déterminé pour chaque type de projet pour simuler les décisions **d'investissement et/ou de déclassement**[1] des acteurs de marché dans des unités de production ou de transport d'énergie. Dans la réalité, ces acteurs font leurs choix d'investissement, et donc de valeur de taux d'actualisation, pour chaque projet spécifique.[2]

Cependant, dans le cadre d'études scénaristiques, ce niveau de granularité est probablement à la fois impossible et inutile à atteindre. Différents niveaux d'agrégation sont alors possibles : l'ensemble du secteur énergétique ou du secteur électrique (European Commission, 2011), une distinction entre mode de production centralisé et décentralisé (PACT, 2011), une distinction par technologie (RTE, 2017), et éventuellement des sous-catégorisations au sein des filières (PV au sol ou en toiture, au Nord ou au Sud de l'Europe, etc.)[3]

[1] Décision de fin de vie d'un actif
[2] Ce taux est ce qu'on appelle un WACC.
[3] Le taux d'actualisation choisi peut être vu comme un WACC agrégé de l'ensemble des projets en question.

Ainsi, RTE dans son Bilan Prévisionnel de 2017 utilise ce type de taux pour « modéliser des investissements sur la base des décisions individuelles des acteurs afin de restituer la logique économique de l'évolution du parc » :

Technologie	Éolien terrestre	Éolien en mer posé	Éolien flottant[5]	Hydrolien marin	Photo-voltaïque au sol	Photo-voltaïque grandes toitures	Photo-voltaïque toitures rési-dentielles[6]	STEP	Cogéné-ration bois-énergie	Cogénération biogaz	Incinération des déchets
Taux d'actualisation	7%[7]	2025 : 7% 2030 : 5% 2035 : 5%	2025 : 9% 2030 : 7% 2035 : 7%	11%	7%[7]	7%[7]	7%[7]	11%	9%	9%	9%

Source : (RTE, 2017)

RTE précise avoir déterminé ces valeurs via une consultation publique.

Explanation box about WACC

WACC stands for "Weighted Average Cost of Capital". It is a rate allowing to integrate the remuneration expected by financers in calculations for a specific project. In other words, it is a discount rate used to include the cost of capital in the evaluation of the profitability of a project. This is why it is sometimes called "capital cost" (whenever a "capital cost" is expressed in %, it is a WACC).

More precisely, a project is considered profitable when its "net present value" (i.e., the sum of all expenditures and revenues, discounted with a WACC) is positive. This means the same project can be profitable or not depending on the WACC value. Therefore the WACC has a significant impact on the profitability of a project. This is particularly true for capital-intensive investments (i.e. projects with high CAPEX and low OPEX) which is precisely the case for REN and nuclear. Therefore, decarbonized technologies viability is very sensitive to the WACC value. Fossil fuels are much less impacted since there are characterized by low CAPEX and high OPEX. Low WACCs will favor decarbonized technologies. It is therefore a key element of the energy transition given our present financing system.

Here is an example to give an idea of how sensible the WACC parameter can be: the LCOE (see LCOE section) of a decarbonized electricity generation unit can double depending on whether the WACC is 0% or 8%. Thus, at 8%, this means that half of the total costs is the cost of capital (these calculations were made for illustrative purpose, for a nuclear power plant with typical characteristics). In the LCOE calculations, this is due to the fact that increasing the WACC does not affect the CAPEX (in the numerator) while it decreases the value of other elements of the ratio.

This enables to understand why WACC choices can have a significant impact on the trajectory of some scenarios.

As described below, the value of the private discount rate, and therefore the value of the WACC, depends on a combination of risks. These risks are related to the country where the project takes place (country risk), its policy (subsidies, risk reduction mechanisms for the financers, etc.), the maturity of the sector and its acceptability (delivery and legal risks). In the case of the WACC, which is a project-specific indicator, its value also depends on the financing structure of the given project (debt-to-equity ratio, corporate finance or project financing structure, etc.)

Le taux d'actualisation privé varie selon différents facteurs.

L'action publique peut intervenir de multiples façons, souvent pour faire diminuer ce taux : politiques d'investissements dans certaines technologies, mécanismes de soutien à certaines filières (contrats long-terme, primes ou tarifs de rachat), etc.[4]

Les régulations et la structure de marché, qui peuvent être impactées par l'action publique mais pas seulement, peuvent être relatives à des périodes de dérégulation ou re-régulation sur le secteur de l'énergie, l'hypothèse d'une renationalisation, le nombre d'acteurs sur le marché et sa 'concentration' (est-ce que les parts de marché sont

4 À titre d'exemple RTE indique prendre un taux qui passe de 7% à 5% avec soutien public pour les filières éolien terrestre et photovoltaïque.

détenus par quelques gros acteurs ou un ensemble de plus petits ?), le niveau des barrières à l'entrée, etc. Les risques de transition associés à la prise de conscience des impacts du changement climatiques sont par exemple voués à augmenter dans les décennies à venir.

Certaines **caractéristiques d'une filière** peuvent faire augmenter le taux d'actualisation privé : faible maturité technologique (risques plus élevés lors de la construction, de l'atteinte des performances souhaitées, etc.), fort impact négatif sur l'environnement (risques juridiques), mauvaise perception de la technologie par la société civile (risques de complications au cours du projet), etc. De plus, la répartition des coûts dans le temps joue un rôle important : les technologies fortement capitalistiques doivent faire face à un gros investissement initial, ce qui les rend très sensibles au taux (WACC) choisi.

Tous ces éléments sont eux-mêmes impactés par le pays dans lequel se déroule le projet (choix dans l'action publique, régulation, …) La disponibilité en financements et le niveau de risque (risque pays) diffèrent grandement selon la santé financière du pays et du taux d'emprunt moyen des banques.

2. Choix des ménages : un taux **d'actualisation subjectif** pour approximer la réalité

Le taux d'actualisation subjectif est utilisé pour simuler le comportement des ménages dans leurs décisions de **consommation ou d'investissement**. C'est un taux implicite, une approximation qui n'existe pas vraiment en réalité (dans la pratique, les ménages résonnent plutôt en termes de temps de retour sur investissement). On retrouve son utilisation dans plusieurs études telles que (European Commission, 2011), (ANCRE, 2013) ou encore (CIRED, RAC-F, 2012) avec **des taux d'**actualisation spécifiques à chacun des types de propriétaires des logements dans le cas d'une décision de rénovation thermique

Les ménages étant supposés plus « myopes » (c'est-à-dire attachant encore plus d'importance au présent qu'au futur) que les acteurs de marchés, ce taux est souvent le plus élevé de tous, de l'ordre de 15-20%.

3. **Choix d'investissements publics** : un **taux d'actualisation public** reflettant une démarche d'**utilité sociale sous contraintes**

Un pan de la littérature sur le taux d'actualisation traite de son usage public.[5] Plusieurs approches existent pour déterminer le taux d'actualisation public souhaitable. Aucune ne fait consensus, et celles-ci varient d'un pays à l'autre, selon la période, et selon les experts (3% et 7% aux Etats-Unis, un taux de 3,5% pour les projets ne dépassant pas 30 ans et qui diminue ensuite au Royaume-Uni, etc.) Pour plus de détails à ce sujet, voir notre note sur le taux d'actualisation (à paraître), ou la note de France Stratégie « Discount rate in project analysis » (France Stratégie, 2017).

Nous ne développons pas le sujet du taux d'actualisation public ici car en ce qui concerne le secteur énergétique, l'Etat n'investit la plupart du temps pas directement dans les unités de production, transport ou stockage d'énergie (comme vu au paragraphe précédent, ce sont les acteurs de marché qui jouent ce rôle). Ainsi, nous n'avons pas d'exemple d'utilisation de ce taux d'actualisation public dans des scénarios énergétiques. Un cas possible serait une situation de renationalisation. En dehors de cette possibilité, l'action de l'acteur public dans ce domaine est d'une autre nature (subventions, aides au financement, etc.) que nous explicitons plus loin.

5 Pour décider d'un investissement public, l'Etat doit lui aussi choisir un taux d'actualisation. Contrairement à la sphère privée, son calcul économique n'a pas pour ambition une maximisation du profit, mais plutôt une utilité sociale. Ainsi, les taux utilisés sont systématiquement plus bas que ceux des acteurs privés. Toutefois, celui-ci évolue dans un monde réel et donc sous contraintes de financement : gestion du déficit public et/ou de la dette, attente de rentabilité de la part de créditeurs privés, etc. Ainsi, le taux d'actualisation public reste plus « contraint » (et donc plus élevé) que le taux d'actualisation social « pur » (en France par exemple, le taux d'actualisation public inclut une prime de risque spécifique à chaque projet).

B. Effectuer des comparaisons du point de vue d'un « planificateur bienveillant » : le taux d'actualisation social

Cette approche se place dans un cadre théorique où le but est d'évaluer et comparer plusieurs systèmes selon le point de vue de planificateur bienveillant, c'est-à-dire selon un principe de maximisation du bien-être social sur l'ensemble de la trajectoire des scénarios en question. Ainsi, contrairement aux taux vus précédemment, on raisonne ici sur un taux "sans risque". Le point de vue du planificateur bienveillant est une sous-catégorie du point de vue 'système' développé dans la section Economic Evaluation.

1. Calculer le coût total d'un scénario dans un but de comparaison

La description d'une transition nécessite des investissements et divers autres coûts année après année tout au long de la trajectoire. Lorsque l'on souhaite comparer plusieurs trajectoires, il est nécessaire de les actualiser afin d'**estimer leur coût total depuis le prisme d'aujourd'hui**. C'est le cas de l'étude (Fraunhofer ISE, 2015), qui évalue le coût total de ses deux scénarios en effectuant une analyse de sensibilité sur ce taux, avec des valeurs allant de 0 à 3%.

Pour ce faire, il faut utiliser un taux d'actualisation reflétant les intérêts de la société dans son ensemble. Comme expliqué dans un prochain paragraphe, le choix de cette valeur relève entre autres de grands choix éthiques. Les valeurs typiques du taux d'actualisation social sont généralement plus faibles que pour les autres taux.

Toutefois, il est important de préciser qu'aucune actualisation ne doit avoir lieu lorsque l'on veut évaluer l'évolution de l'effort financier d'une trajectoire. En effet, cela écraserait les coûts. Cet élément est approfondi dans la section Economic Evaluation.

2. Le taux d'actualisation social vu comme un arbitrage entre trois effets

Ce taux soulève de nombreuses questions, dont certaines sont d'ordre éthique voire philosophique, notamment au sujet de notre responsabilité vis-à-vis des générations futures et donc de la tendance court-termiste de notre société actuelle qui ne lève pas assez le regard sur les enjeux de long-terme.

La question est donc de définir la valeur désirable de ce taux. Une grille de lecture intéressante pour décomposer le taux d'actualisation social est de le voir comme un arbitrage entre trois effets[6] (Percebois, 2012) :

- un **effet d'impatience**. Celui-ci correspond à une préférence 'pure' pour le présent. Cela inclut à la fois le fait que nous préférons consommer aujourd'hui plutôt que demain, et le fait qu'une catastrophe de probabilité infime – mais réelle – puisse venir bouleverser toutes nos anticipations. Dans les deux cas, cela incite à accorder une valeur supérieure au présent qu'au futur. Ainsi, ce terme prendra toujours une valeur positive.

- un effet de richesse. Si on projette que les générations futures auront plus de facilité à assurer leur bien-être que nous et vivront plus longtemps, il faut déterminer ce que la génération présente devrait « sacrifier » en termes d'investissements qui bénéficieront au futur. Pour cela, certains font des hypothèses sur la croissance économique. Plus on croit que celle-ci sera forte, plus le taux sera élevé et estompera l'avenir dans les calculs.[7]

- un effet de précaution. Il convient toutefois d'une part de « prendre de la distance » avec les estimations de croissance : l'incertitude croît avec l'horizon temporel. D'autre part, il ne faut pas laisser à nos descendants un

[6] On peut quantifier cet arbitrage via la « règle de Ramsey ».

[7] Notons que ce calcul avec une valeur unique de taux n'a de sens que si on suppose une croissance assez stable. Si on prévoit par exemple que la richesse augmente sur 20 ans, puis chute sur les 20 années suivantes, il faut utiliser un taux variable qui suit cette estimation. La formule d'actualisation doit alors être modifiée en conséquence.

environnement dégradé.[8] L'effet de précaution permet donc de « corriger » l'effet de richesse, en venant diminuer le taux à mesure que l'horizon de temps augmente. (Gollier, 2016)

NB : le taux d'actualisation social est un taux « sans risque ». Il est parfois confondu à tort avec le taux d'actualisation public, qui contrairement au taux social doit prendre en compte certaines contraintes du monde réel, et peut ainsi parfois se calculer selon la même philosophie que le taux social auquel on ajouterait une prime de risque. Pour plus de détail, voir (France Stratégie, 2017), ou notre note sur le taux d'actualisation (à paraître).

3. La nécessité d'intégrer le long-terme en retenant des valeurs basses voire négatives

Malgré la multiplicité des approches, l'utilisation d'un taux social bas (1,5%, 0%, voire négatif[9]) est de plus en plus recommandée compte tenu des grands défis systémiques de ce XXIème siècle (Bovari, Giraud, & Mc Isaac, 2018; Fraunhofer ISE, 2015; German Federal Environmental Agency, 2012; Grandjean & Giraud, 2017).

Encore une fois, on retrouve ici l'idée que le facteur principal impactant la valeur du taux d'actualisation social est notre croyance sur la croissance économique à très long-terme.

Recommandations pour les producteurs de scénarios :

Lorsqu'un taux d'actualisation social est utilisé, la valeur retenue devrait être justifiée en lien avec les projections (explicites ou implicites) de croissance économique du scénario.

La valeur du taux d'actualisation social utilisé est-elle mise en lien avec des projections de croissance économique ? Quelles sont ces prévisions ainsi que leur niveau de certitude ?

Ainsi, il peut être intéressant de simuler un cas de figure avec une croissance économique faible ou négative via un taux d'actualisation social aux valeurs très basses voire négatives. Dans le cas d'une croissance non monotones, il peut être intéressant d'expliciter la méthodologie utilisée.

Quelle valeur retenir et quelle méthode de calcul dans le cas d'une croissance forte suivie d'une stagnation et d'une décroissance ?

III. Synthèse des facteurs influençant la valeur du taux d'actualisation

Le tableau suivant présente les différents types de taux d'actualisation accompagnés de plages de valeurs, et synthétise les principaux facteurs ayant un impact sur ces valeurs, avec une distinction dans l'ordre de causalité entre facteurs 'initiaux' impactant eux même des facteurs 'finaux' :

[8] L'indicateur PIB ne permet pas de rendre compte de l'état du climat, des sols, de la disponibilité des ressources non renouvelables, etc.
[9] (Bovari, Giraud, & Mc Isaac, 2018): *« [...] because a world breakdown might be the prospect that markets should start facing from now on. If the next generation is going to be less wealthy than we are today, then a US dollar today should be worth less than the same dollar in a couple of decades. »*

Facteurs 'initiaux'	Facteurs 'finaux'	Valeur impactée	Acteur concerné et plage de valeurs 'typiques'	
- Suppositions sur la 'nature humaine' - Prévisions et incertitudes sur la croissance à long-terme	Choix vis-à-vis : • de l'effet d'impatience • de l'effet de richesse • de l'effet de précaution	Valeur du taux d'actualisation sans risque	Planificateur bienveillant *Taux social* <0-5%	Etat *Taux public* 1-8%
- Action publique - Régulations - Structure de marché - Caractéristiques du secteur / de la filière en question	• Disponibilité / capacité de financement • Risques, perception du risque, aversion au risque	Valeur du taux relatif aux attentes de rémunération des financeurs	Acteurs privés *Taux privé* 5-15%	
		Valeur du taux relatif à l'optimisation du budget du ménage	Ménages *Taux subjectif* 15-20%	

Figure 2 : Tableau récapitulatif des quatre différents taux d'actualisation, avec des plages de valeurs 'typiques' et les principaux facteurs permettant de définir ces valeurs

L'approche de planification bienveillante utilise exclusivement le taux d'actualisation social, tandis que les acteurs privés utilisent un taux relatif aux attentes de rémunération des financeurs. Pour les ménages, la logique simplifiée est que pour les acteurs privés, mais leur taux subjectif est plutôt relatif à une optimisation de leur budget. Leur comportement est moins rationnel et la dimension psychologique est plus forte (aversion au risque, perceptions, influences, …) L'acteur public peut utiliser une combinaison de facteurs selon le point de vue choisi.

Recommandations pour les producteurs de scénarios :

Lorsque des taux d'actualisation sont utilisés, les valeurs retenues devraient être explicitées et justifiées. Ces choix de valeur devraient être mis en cohérence avec les choix d'usage et d'acteurs concernés. Ils peuvent en effet être dimensionnants dans certains scénarios.

Quelles valeurs de taux d'actualisation sont utilisées ? Quels facteurs influencent ces valeurs, selon l'usage et l'acteur concerné ? Par exemple, dans le cas de décisions privées, quelles sont les régulations, la structure de marché ; l'Etat met-il en place un mécanisme de soutien d'une filière ?

Les causes de l'évolution potentielle d'une valeur au cours du temps peuvent être explicitées.

Dans le cas de décisions privées, si une filière gagne en maturité au cours du scénario, dans quelle mesure faire diminuer son taux ?

Enfin, afin de mieux éclairer dans quelle mesure ces choix sont dimensionnants (et puisqu'il n'existe pas de consensus sur ce que devrait être les valeurs de taux d'actualisation), des analyses de sensibilité sur le taux d'actualisation devrait être menées et présentées.

IV. Bibliographie

ANCRE. (2013). *Scénarios de l'ANCRE pour la transition énergétique*.

Bovari, E., Giraud, G., & Mc Isaac, F. (2018). Coping With Collapse: A Stock-Flow Consistent Monetary Macrodynamics of Global Warming. *Ecological Economics*, *147*, 383-398. https://doi.org/10.1016/j.ecolecon.2018.01.034

CIRED, RAC-F. (2012). *Building a low-carbon scenario for France - How a participatory approach can enhance social and economic acceptability*.

European Commission. (2011). *Energy Roadmap 2050 - Impact assessment and scenario analysis*.

France Stratégie. (2017). *Discount rate in project analysis*.

Fraunhofer ISE. (2015). *What will the energy transformation cost? - Pathways for transforming the German energy system by 2050*.

German Federal Environmental Agency. (2012). *Methodological Convention 2.0 For Estimates Of Environmental Costs*.

Gollier, C. (2016). Valorisation des investissements ultra-longs et développement durable. *L'Actualité économique*, *92*(4), 667. https://doi.org/10.7202/1040502ar

Grandjean, A., & Giraud, G. (2017). *Comparaison des modèles météorologiques, climatiques et économiques : quelles capacités, quelles limites, quels usages ?*

PACT. (2011). *Post carbon transition scenarios*.

Percebois, J. (2012). *La lettre de l'I-tésé*, (16).

RTE. (2017). *Bilan prévisionnel de l'équilibre offre-demande d'électricité en France*.

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The Shift Project

The Shift Project, a non-profit organization, is a French think-tank dedicated to informing and influencing the debate on energy transition in Europe. The Shift Project is supported by European companies that want to make the energy transition their strategic priority & by French public funding.

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