Future studies
on energy transition

Technical file #1

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 nearly 2 years of research and experts consultations on the different aspects of energy transition and the future studies around these aspects.

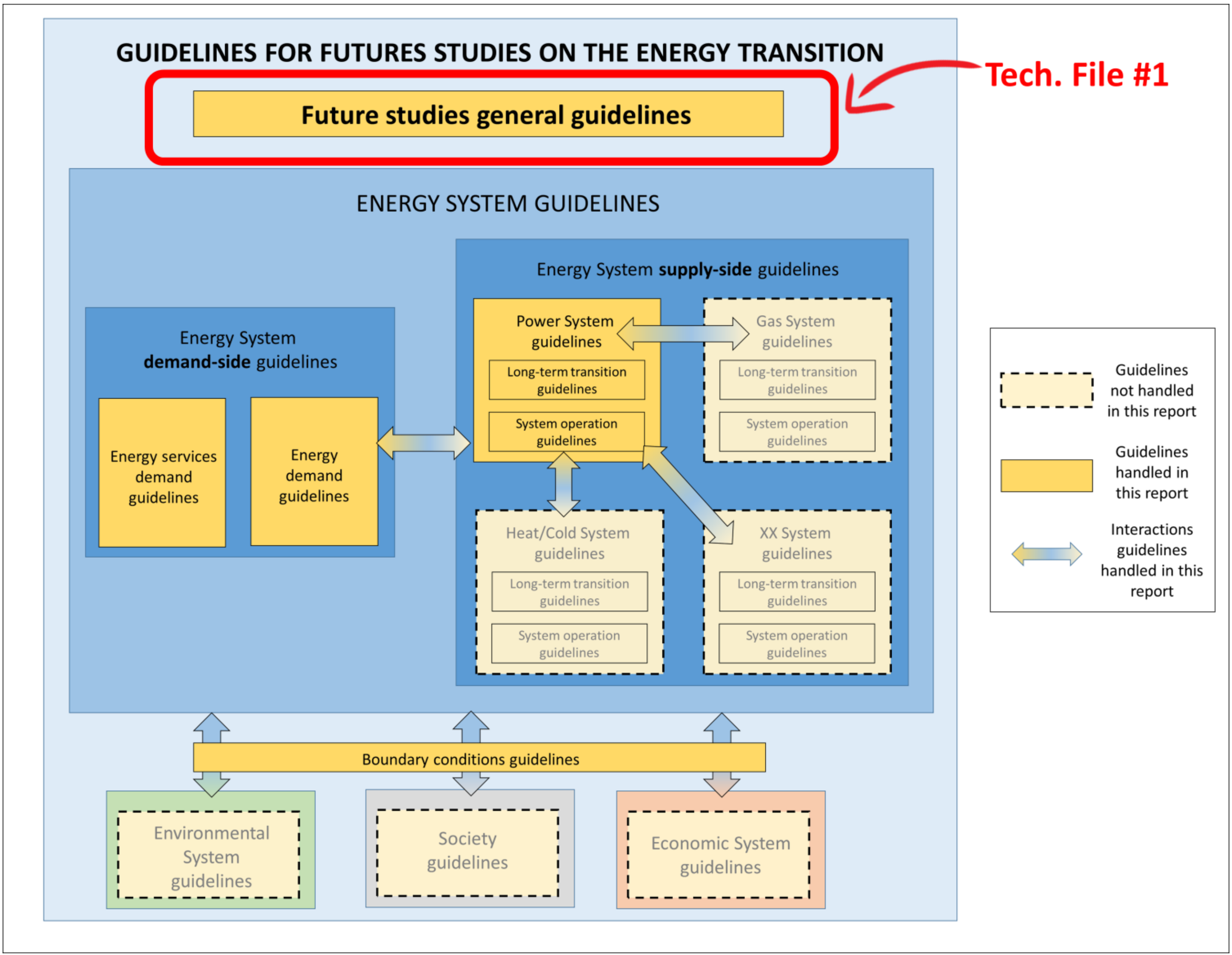
Our project, "Power Systems 2050 – Guidelines for future studies on energy and power transitions," started in January 2018, involved approximately 60 experts through interviews and workshops, reviewed more than 300 works, including about 20 future studies. The objectives and approach of this project are discussed in the executive summary of the framework.

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 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.



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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. 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).

Under our scope, 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 and activities which are described must be consistent; for example, lifestyles and cultural trends, technological progress, resources availability, environment, institutions should 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 mostly qualitative *storyline*, which is then translated into figures feeding a *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).

The *results* published in a study are composed of

- the interpretations of selected outputs from the model for each scenario;
- consistent stories (one for each scenario) built by merging these interpretations with the associated storyline and hypotheses;
- conclusions based on the comparisons between those stories;
- recommendations based on all the preceding results.

B. Future studies are political objects aiming 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 ideas or more generally their behaviors 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 ideas, speeches and behaviors after reading, or hearing about, the study.
- **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 (Stern, 2017). It seeks to carry a message about the future evolution of the system it studies. Due to their forward looking nature, their object (the evolution of human systems) and their public status, **future studies included in our scope are political objects per se**.

As a consequence of this scope for our framework, considerations about why and how policy makers make their decisions is out of the scope of the future studies we include (Cherp, Vinichenko, Jewell, Brutschin, & Sovacool, 2018). These future studies assume the role of policy-makers by presenting, discussing and often proposing policies or actions that could be undertaken at the political level. The underlying assumption of the future studies we address our framework to is that policy makers are influenced by such future studies to inform their decisions.

C. Our scope: future studies dealing with power systems and addressed to policy makers and to 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). Interactions between the energy system and several surrounding systems[1] can be found in (Droste-Franke et al., 2015).

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).

[1] They include the geo-scientific system, natural systems, agricultural systems, forestry systems, legal system, economic systems, social or education system, political system.

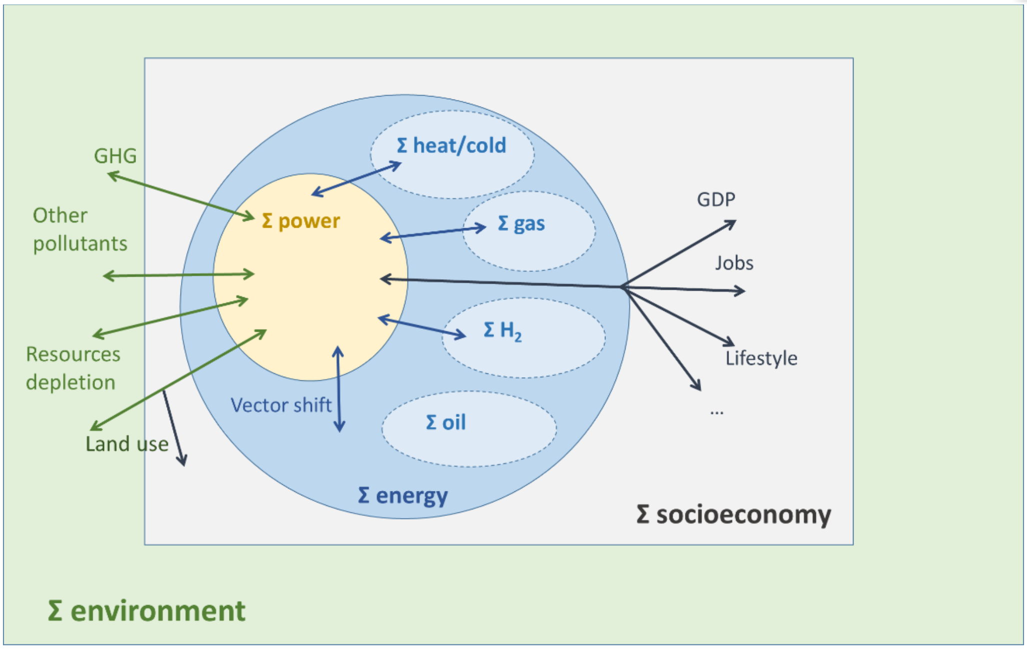

Figure 1: The environment is the ground for human societies to live, produce, transport, exchange and consume goods and services (which is called the socioeconomic system here). A part of the socioeconomic system is the energy system, in which energy is produced, transported, exchanged and consumed. 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.

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 (outputs) which are interpreted by scenario producers.

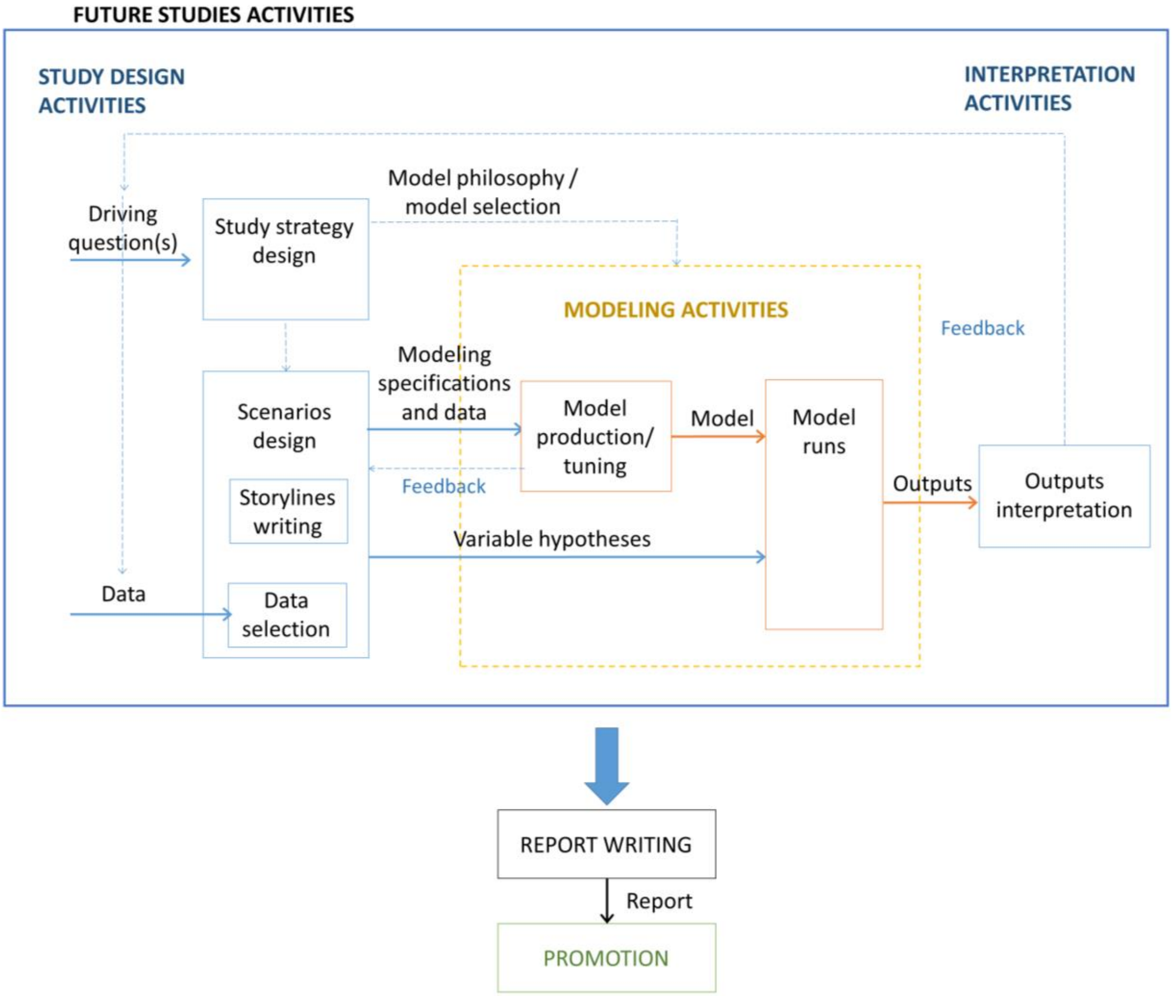

Figure 2: The different steps of future studies production, from study design activities to promotion.

Often, scenario producers discover from these outputs 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. Writing this report requires to interpret outputs, chose which elements to publish and shape narrative elements based on the hypotheses and outputs, in order to build a consistent story for each scenario. These stories are compared in order to draw useful conclusions, and sometimes derive recommendations for the target audience.

All these activities require various fields of expertise, depending on the scope of the study:

- Content expertise gathers energy system experts from different fields (expertise on different energy system's components, on energy consumption…), environment experts from different fields (air pollution, climate change, biodiversity…), economists, sociologists and psychologists;
- Cross expertise gathers future studies experts, computational programming experts, communication experts, graphic design skills and so on.

These activities are in some cases performed by different actors. Some associations or non-governmental organizations (NGOs)[2], think tanks[3], foundations[4], public agencies[5], companies[6] or individuals engage in future

[2] Negawatt, Sauvons le climat, Réseau Action Climat – France, WWF, Greenpeace…
[3] The Shift Project, Agora Energiewende…
[4] European Climate Foundation…
[5] ADEME, European commission…
[6] EDF, RTE…

studies activities and/or modeling works. Some companies[7] or research laboratories[8] 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[9] publicly provide, or sell data about the current state of the world.

E. Our goals: uncovering the map of the energy transitions respecting the laws of physics…

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 to help societies decide 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.

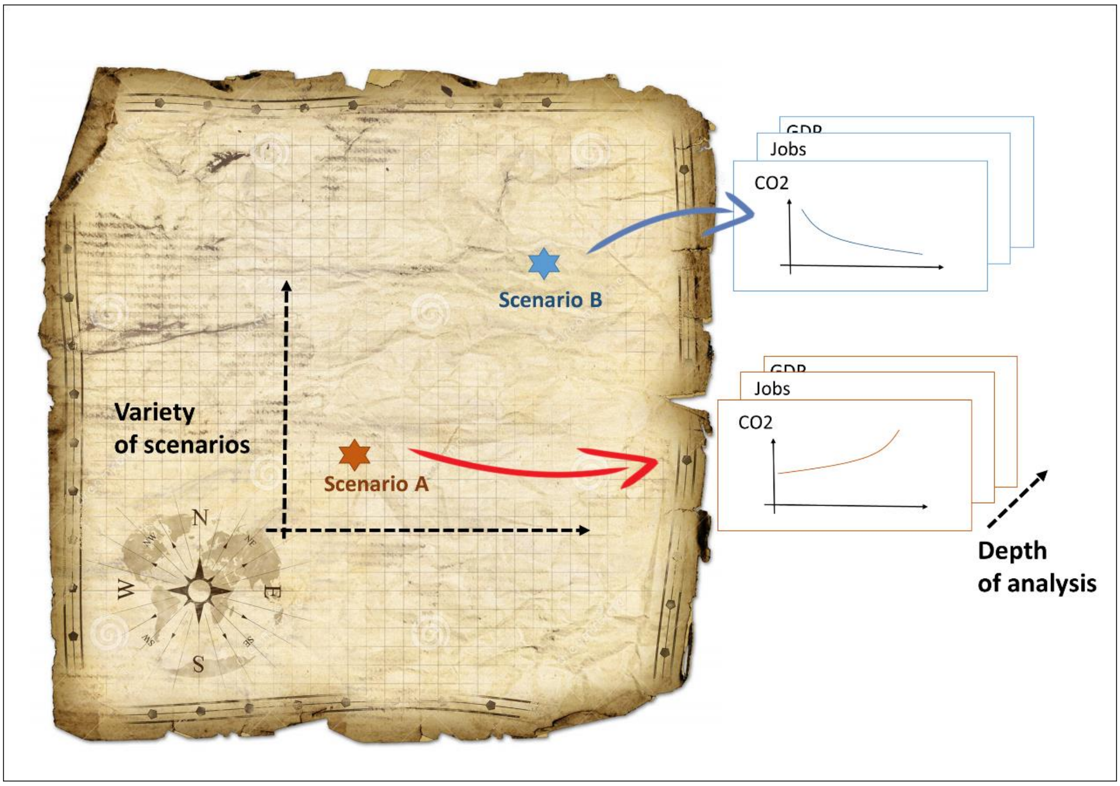

Figure 3: The transition map indicates the different worlds we can decide to head to. The role of future studies is to uncover the transition map as much as possible, in terms of scenarios diversity and depth of analysis (diversity of considered variables). Source: The Shift Project. Image: dreamstime.com

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 collaborative and constructive way. This would place them on the same transition map and help the reader quickly uncover the parts of the map informed by the different future studies.

This framework deals with energy system transition scenarios. The energy system is composed of a physical system[10] and as such it follows the laws of physics, most of them being well known by physical science. Our

[7] Enerdata, Artelys E3-Modelling…

[8] Centre de mathématiques appliquées (CMA) at Mines ParisTech, Laboratoire d'économie appliquée à Grenoble (GAEL), Joint Research Center (JRC)…

[9] Enerdata, IEA, The World Bank, OECD, GaBi…

[10] However this physical system widely interacts with surrounding systems: society, the economy and the environment.

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.

F. …And reinforce and connect existing scenario communities

The future study 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.

Future study stakeholders seek to inform and influence the energy transition debate. They form teams for producing specific future studies; they gather and share information around specific models[11]; they occasionally gather for events to share modeling practices[12]; some produce collaborative platforms to share data (such as the Open power data platform (Wiese et al., 2019)) and/or models (such as the openmod initiative).

However, the different teams and projects rarely coordinate in their effort to inform the energy transition debate, which is one reason why we decided to build the present methodological framework.

For the time being, at national level scenario teams gather for some special occasions, such as particular political processes[13]. 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 (ANRT/FUTURIS, 2019). Similarly, they would discuss, share and improve energy system models, reducing parallel efforts and duplication of work. They would collaboratively consolidate released codes and implement standards for their interoperability and legibility (Pfenninger, DeCarolis, Hirth, Quoilin, & Staffell, 2017). 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, concrete descriptions addressed to stakeholders, as well as transparency in the interests of each member of the community are the key components of this ground.

1. Transparency for a healthy energy transition debate: being transparent on key data and methodology, being concrete about key impacts for each transition stakeholder

Several critiques are formulated concerning published future studies. The main one is that future studies actually embed values without clearly revealing them. Studies reflect these values even when they are produced by research institutes (supposedly applying neutral science), because these institutes are linked by a contractor-client relation to study financers (Schubert, Thuß, & Möst, 2015).

It comes as natural that study financers (or study producers if the study is not ordered) embed their own values in the model they use, in the hypotheses they take, in their interpretation of results, in the whole narrative finally produced and in the recommendations. For example, Nordhaus and Stern disagreed about the discount rate that should be used in Integrated Assessment Models (IAMs): the former thought market values should be used whereas the latter thought very low values reflecting inter-generation equity should (Nicolas, 2016). This should not be seen as a problem, insofar each of them makes his choice explicit.

This critique is even more profound when it comes about the functional structure of complex models which are used to produce studies: these structures also embed the values of those who financed or designed the model. However, their complexity prevents from a complete and clear understanding of the values they embed. For instance, a classical critique about IAMs is that they assume the way some human systems operate, the

[11] Such as IEA-ETSAP community sharing data and good practices around the TIMES model
[12] Such as events organized by the Energy Modeling Forum by Stanford University
[13] 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.

environment, etc., will not change significantly. Indeed, these models are calibrated on what is observed today: the finance system is modelled as it is currently operating, climate change has no impact on the economic structure, growth goes on, etc. Hence these models may be described as embedding "status quo" values (Morgan & Keith, 2008). Other models may embed other types of values.

In order for the energy transition debate to be as healthy and democratic as possible, transparency on these aspects is key.

Transparency pertains to the providing of data, but also to the way these data are provided. Too much data, or poorly organized data do 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).

Adapting transparency to the target audience can be achieved through discussion with the different stakeholders so as to produce a speech which they easily understand.

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, projects launched within the JRC target the second level of data publication (large 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 transparency on the data and methodology 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).

In our views, this first level of transparency is absolutely necessary to foster a healthy energy transition debate. This debate is crucial as it virtually involves 100 % of the population in all the different aspects of their lives (as consumers as well as producers) for the next decades**. If we want to call this debate a democratic debate, a high level of transparency must be reached**.

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 is not only 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.

In this framework **we also insist that justifications are provided for the various choices made by the study producers about their methodologies, the models they used, their hypotheses and so on**. This increases understanding and thus trust in the reader. It also reveals the possible difficulties producers had on some aspects, such as lack of reliable data or lack of available models. As these difficulties likely apply to many other study producers, the community may be more compelled to overcome them than if they remain untold.

For instance, 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 works. This work is so complex that no team engaged in this process so far. By being transparent on their strategy about impact assessment on biosphere, study producers may collectively acknowledge this difficulty and find common solutions (such as allowing qualitative assessments, sharing methods).

b. Our framework fosters useful and efficient descriptions of transitions through concrete enough narrative elements

We call *concrete description* of an event (or part of a transition), 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** (Saltelli & Funtowicz, 2014). 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 data produced by the model or be at the origin of data that are inputs to the model. In any case, the concrete description should be consistent with those data.

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 lighting of lightbulbs will decrease by 10 % does not tell much about how it will materialize in the lives of households or companies. Now, saying that people will always shut off the light when they are not in a room is a more concrete description which may correspond to this same 10 % reduction. However, in order to deduce that 10 % of the lighting corresponds to systematically switching the light off in households, the scenario producer needs to collect data about the actual use of lighting (hence data about ways of lives of households), 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 climate experts, but may not be concrete enough for the greater public (the laypeople, including decision makers, may not concretely understand what such an increase would mean for them and for society). For the greater public, more concrete depictions of weather events which happens at this average temperature would be necessary.

Producing concrete descriptions is a challenge for scenario producers. The reason is, 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.

Indeed, many models are originally designed to bring information about the link between economic activity development and its associated impacts on climate. Some 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 they make it 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…).

As a results, extra-steps, and extra hypotheses, to go from model variables to more "concrete" narrative elements are required. 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.

Implementing a participatory approach with different stakeholders to discuss hypotheses and results fosters the production of concrete descriptions as all the stakeholders should be able to understand and discuss the studied topics. Thus these topics must be prepared and described in that purpose.

Fostering transparency trough concrete descriptions of interactions with surrounding systems is a critical objective of this framework.

c. 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 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[14]) are not directly collected by scenario producers: they come from other public, or private sources. If they are publicly available, providing their sources 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[15] can be cumbersome.

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

- Be able to discuss the data, improve and update datasets 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 steel required to build wind turbines (expressed in kg/kW of installed wind turbine) can be measured over different geographical areas (is the measure performed on turbines installed in Germany or in China?). It can also be measured over different functional scopes (is the measure performed on a scope which is the tower and turbine only, or which also includes its foundations, or even including the road which had to be built to access the turbine?). It can be measured over different time scopes (is the measure performed on turbines installed during year 2023 or over the years 2026-2031?).

To go even deeper in data publication, the NUSAP methodology (Saltelli & Funtowicz, 2014) proposes to use five qualifiers to describe a quantity:

- The numeral value of the quantity
- Its unit
- Its spread (a measure of statistical or measurement error)
- Its assessment (a quality check of the three previous data by experts of the field)

[14] See box below and Figure 8 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.

[15] See box below and Figure 8 for definitions: endogenous variables are those data which are assumed in the model to be affected by other variables or parameters.

- Its pedigree (which is an assessment of the overall methodology used to obtain the data: modeling, data acquisition, expert elicitation and so on)

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 (Pfenninger et al., 2017; Wiese et al., 2019).

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

In the field of power system modeling, an effort to promote data publication on a shared platform (Open Power System Data platform) in a standardized and readable way can be found in (Wiese et al., 2019). This project collected, checked, processed, aggregated, documented, and published data sets for power systems modeling.

d. … 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, its history, provide the questions it has been designed to answer to, and compare its main differences with other models, through text and diagrams. This requires a simple description of the model, hence it requires experts' choices about what to include in this simplified description (see next subsection, and more details in section about models). 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 functional explanation is already provided in most scenario reports. However, limitations of the model, and justifications on the fact it can be used to answer the driving question are rarely provided.

- 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, or the values embedded in it, 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 readable (e.g., 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.; Capros 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).

More considerations on data and model publication (intellectual property, publication licenses, modelling tools and langage, code and data accessibility once published, support and community building) can be found in (Pfenninger et al., 2018).

Recommendations for scenario producers

A scenario strategy about transparency should be defined and justified (Cao, Cebulla, Gómez Vilchez, Mousavi, & Prehofer, 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? What data are not published? Why are these not published? Are some of them already published by another organization?*
- Endogenous data publication coverage. *How much of the endogenous data has been published? What data are not published? Why are these 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. The type of questions the model had been designed to answer to in the first place should be made explicit.

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. Explaining in a simple way the model and its outputs

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. Most criticism and distrust towards energy transition future studies comes from a lack of explaining simply the results.

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.

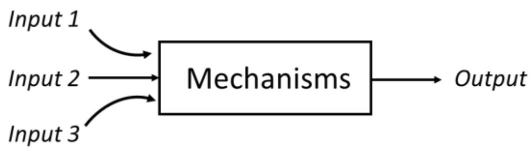

Figure 4: Ideally, main outputs should be explained by a few inputs (exogenous variables) and a few model mechanisms. Popularization can be achieved by explaining how these inputs interact in the model.

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 provide the minimal amount of information required for non-experts to properly understand the results and explain them in their fashion. 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.

b. 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. Furthermore, the energy system interacts with even more complex systems. 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, the more complex a model, the more its 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 properly answer the driving questions. In theory, driving questions determine model complexity, which determines how difficult popularization will be. In practice though, many studies use off-the-shelf models. This implies, at best, that the model is more complex than it should (they "used a tank to kill a fly"), and at worst that it should not have been used for answering their driving questions.

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 model outputs. *Are important outputs simply explained through (a few) links between key hypotheses, key model mechanisms and the outputs?*
- Outputs still to interpret. *Are some important outputs 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. Increasing credibility through disclosure of interests, stakeholders' involvement and disclosure of study limitations

Future studies should disclose any conflict of interest.

They deal with the future of societies and are political objects by nature, seeking to carry a message to a target audience. Transparency about who carries the message and to whom the message is addressed is key for the reader to fully understand the context in which the study takes place. As commonly performed in academic research studies, disclosure of interest is even more crucial for scenario production: 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). The same disclosure should apply for models used (including off-the-shelf models).

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 and within the reader. During these sessions, hypotheses and results can be questioned so that scenarios' designs can evolve. This approach both improves transparency (hypotheses and results are transparently discussed) and credibility (various expertise fields and interests are represented).

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, as already discussed.

Finally, including a section listing all the limitations of the study (including the limitations arising from the model which has been used) 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 disclose in their study report as well as in the associated executive summary the following information:

- their funding sources;
- all members who participated in the study (individuals as well as the organizations they represent) along with their potential financial interests linked with the study;
- how stakeholders or experts have been included in the study production process.

They should also disclose who designed the model they used, and the funding sources at the origin of this model.

Scenario producers should report about the limitations of their study (including the limitations arising from the model which has been used) in a dedicated section of their report. Limitations can be detected through expert knowledge or any other means such as the present guidelines.

Several studies have proposed good practices and recommendations for scenario producers e.g., (Cao et al., 2016; Child, Koskinen, Linnanen, & Breyer, 2018; Droste-Franke et al., 2015; Saltelli & Funtowicz, 2014; TCFD, 2017; Tourki, Keisler, & Linkov, 2013). Our framework builds on them, and goes beyond by extending the recommendations to detailed aspects of the energy transition and of power systems transitions.

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. Being transparent on the driving questions and on the context in which they are asked

Different studies generally ask different driving questions. The driving questions directly depend on the political decision process targeted by the study or on its target audience. 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?[16]

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?[17]

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?[18]

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.

[16] This question could be the driving question of (ANCRE, 2013)
[17] This question could be the driving question of (European Commission, 2011)
[18] This question is the driving question of (ECF, 2010): p6.

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[19], or try to reveal the consequences of following different pathways along selected dimensions (for example, GHG emissions, or unemployment, etc).

Most often, future studies are produced in order to inform and influence a specific policy debate or agenda, a specific political process, or law making process. Hence their driving questions are tuned to properly inform this specific process and convey the appropriate messages.

In many studies we reviewed, the driving questions and the context in which they take place are properly described.

For some studies produced by States, groups of States (the European Union), or intergovernmental organizations, the context is clearly described (typically, informing long-term objective settings and short-term action that can be performed in line with those objectives), but the questions asked by the study are not clearly expressed: they are diluted over several pages bit by bits, in different paragraphs.

One of the reasons might be, these actors must remain very "neutral," even though by essence future studies cannot be neutral (they necessarily take a specific approach to answer specific questions with a few selected scenarios). Providing the questions these studies seek to answer would need to define more clearly the choices made and the points of view (necessarily) adopted. As many different stakeholders are consulted for constructing these "neutral" studies in a "bottom-up" way, it may be very difficult for scenario producers to find out themselves what points of view they developed. However difficult it is, making the driving question clear is key for being able to place these studies among the myriad of published studies, and for making them more understandable and accessible to citizens, businesses etc. The developed points of view can be detected through the various stakeholders who have been consulted (what stakeholder categories have been consulted, in what proportions), through the various models used (what type of models, what possible biases these models have), through comparing the study strategy with other studies...

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 et al., 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?*

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

- 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 CO_2 emissions reduction at low cost and influence decision makers towards measures favoring nuclear power development. Etc.*

B. Detailing the scopes and trajectory approach of studies

The scope of a study is composed of its time horizon (including considerations on the trajectory approach), its geographical perimeter and its sector perimeter.

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. In other words, the choice of time horizon is greatly driven by the current political agenda (Lezais, 2015).

However, as developed in the following subsections, 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[20] (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).

[20] 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).

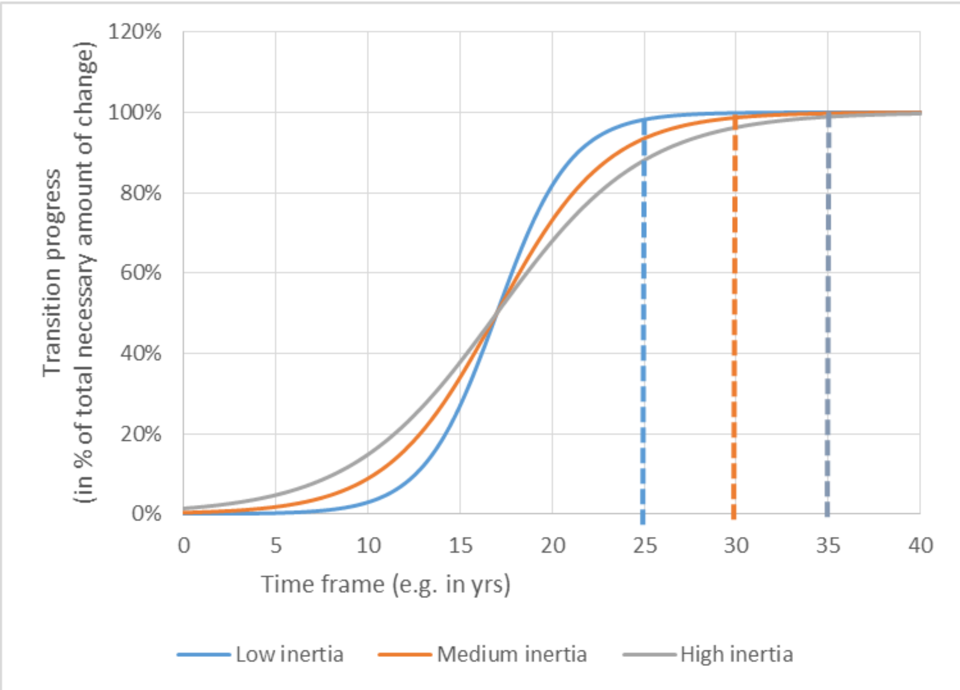

Figure 5: Illustration of what could be the minimal time horizon for different scenarios depending on the inertia of the studied system. Year 0 represents the start-year date. For the low inertia system, transition is quicker hence the time horizon could be as soon as year 25. On the contrary, for the 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[21] as drivers for transitioning (a review is performed in (Child et al., 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 CO_2 emissions reduction target by 2050. After running a scenario until 2050, the CO_2 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 CO_2 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 should be justified with regards to the following considerations: the driving questions of the study; inertia of the described system; planetary boundaries or any other urgency issue; decision-making process which is targeted and time horizons which are considered for this process.

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 of a study corresponds to the geographical area over which the activities described by its scenarios take place. We call this perimeter 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

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

example, "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 study 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 study 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 the 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 system*. Within our framework, the core system is the set of elements and activities related to the technical energy system.

- 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 internal combustion engine (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.

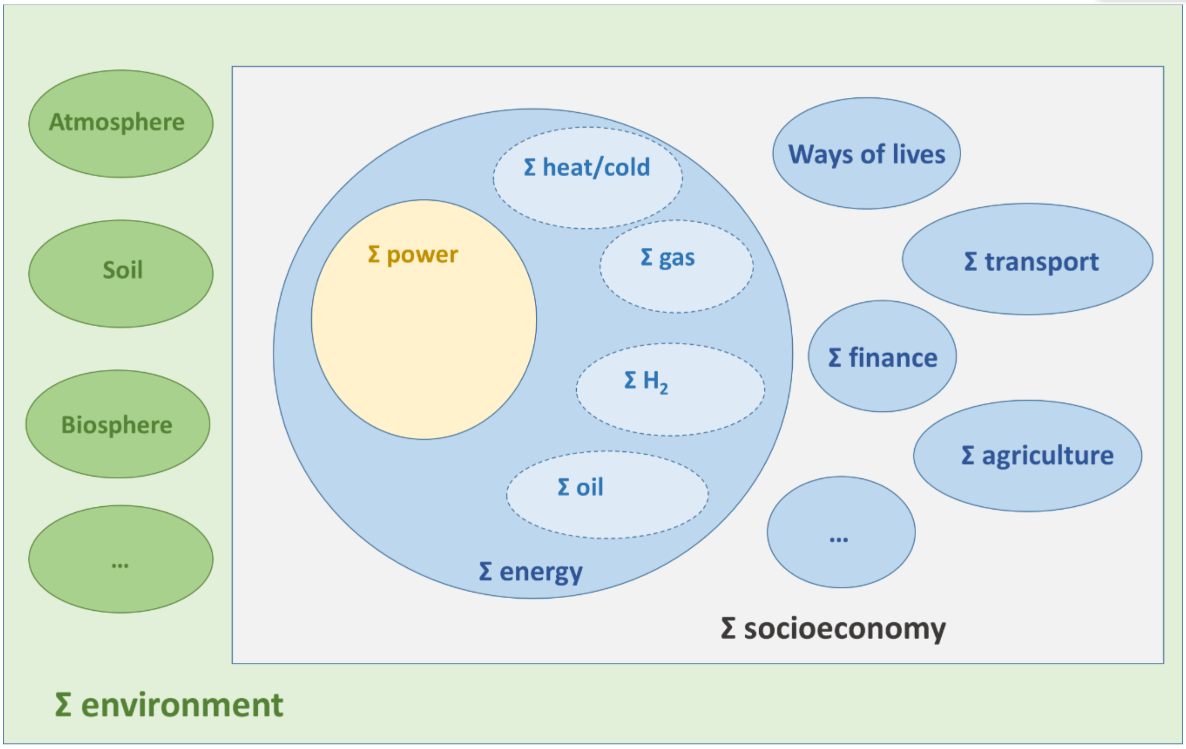

Figure 6: The scope of studies can include all or some aspects of the systems described in this figure. Core systems are included in the energy system. The energy system is the technical system providing useful energy to consumers; it includes the technical infrastructure and equipment on the supply side and on the demand side (consuming devices). Other systems are considered as surrounding systems. The "Σ" symbol means "system" in this diagram.

Around the selected *core system*, 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) may be described (see Figure 6). As the core system evolves, surrounding systems co-evolve with it, because they interact with each other.

Some of these interactions may be described as hypotheses, in which case they are typically referred as "boundary conditions" (conditions of the systems around the core system which are set by hypothesis and which influence the evolution of the core system, see section on boundary conditions) or as results, in which case they are typically referred as "impacts" (impacts of the evolution of the core system on the evolution of surrounding systems, see III.B).

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 and justified with regards to the driving question. 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[22]. 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. 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)).

[22] 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

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.

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 also 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.

Some analyzes and recommendations presented in this guideline apply only to brownfield scenarios, as these scenarios are more complete than greenfield ones (they take into account observed extra constraints, namely, the present state of the energy system). Hence, covering the recommendations on brownfield scenarios also covers all the recommendations which can be made on greenfield scenarios.

C. Using an appropriate model to answer the driving questions

1. Justifying the choice of model among a large variety of models with a variety of abilities and limitations

Future studies generally use computational models to produce internal consistency within each of their scenarios. For example, models ensure minimal consistency between energy production and energy consumption (usually year by year within the scenario timeframe), between energy production and CO_2 emissions, or between the energy mix transition and employment involved in it.

Several different models exist. Some are "of-the-shelf" models and can be used by different future study producers, such as PRIMES, POLES, Artelys, METIS, TIMES, MedPro, MESSAGE... Some others have been designed by the teams using them: Antarès (RTE), the World Energy Model (IEA), négaWatt model (Association négaWatt), REMod-D (Fraunhofer Institute for Energy Solar System)…

Among all those possibilities, it is key that scenario producers select, or design, a model able to answer their driving questions. Key aspects are detailed in the section about models: modeled entities and mechanisms making them interact, aggregation level of these entities, and time and space resolutions.

Models are often extremely complex and the transparency about them is not sufficient to make them understandable even by energy transition specialists. Models embed several hidden limitations, either reflecting modelers' ideologies and/or interests, or being purely technical limitations. Scenario producers must be aware of these limitations to interpret and communicate transparently their results.

Here are some typical limitations of models:

- Power system models with a low resolution of the distribution network: these models cannot properly answer questions about significant changes in the architecture of the power system, such as a transition from a centralized power system to a decentralized one (also see section on power system long term transition). Extra analysis should be provided to answer these questions, such as questions on costs, or power system security of supply;
- Power system models focused on supply-side: these models cannot properly answer questions about policies targeting electricity demand. Extra analysis should be provided to answer such questions as the carbon impact, or cost, of such policies.
- Purely technical models (no macroeconomic loop): these models cannot properly answer questions about rebound effects, employment, or purchasing power. Extra analysis should be provided to answer such questions.
- Models computing demand through a hypothesis on gross domestic product (GDP): these models have a very low resolution on demand behaviors (equivalently, demand behaviors are much aggregated). They cannot properly answer questions about concrete behavior changes. Here again, an extra analysis should be provided to tackle these questions.
- Models calibrating economic behaviors (of households, finance, companies…) based on behaviors observed in the recent past and happening in recent past markets (such as models using elasticity coefficients, or utility functions): these models are based on the idea that economic agents will behave in a much similar way as what is observed today in our current markets, and with similar preferences (PRIMES model is one of them, as described in (European Commission, 2011)); as such, they may not be able to answer questions about strong transitions, such as markets structures changes, cultural changes, or policies fostering new consumption behaviors and biasing so-called free-markets (e.g. incentives for consuming less, or consuming long-lived, or low impact products through State advertisement), investment behaviors based on ideologies other than that of free markets (such as divestment movements) and so on.
- Models requiring a GDP input for determining demand and production: those models derive from models designed in the 70's as a reaction of the future study by the Club of Rome "Limits to Growth"; this study concluded that infinite growth is not possible with a finite set of resources and a finite ability of the environment to absorb pollutions. In reaction, pro-growth economists designed models answering such questions as "what is the best growth?" (as described in (Nicolas, 2016)). These models try to compute the conditions to sustain a given growth, and they now integrate a few constraints that can be activated by scenario producers, most typically a constraint on carbon emissions. Hence they cannot properly answer questions about other physical limitations (material resources availability, biodiversity…), or questions about de-growth policies or cultural evolutions leading to de-growth.

These limitations are sometimes not respected by scenario producers. Very often, they are not acknowledged in reports, hence not transparently declared. Limitations seem to be fairly respected by scenario producers, but they still limit the range of questions scenario producers can ask. For instance, scenario producers using models requiring a growth hypothesis must suppose… growth. This tends to make hypotheses about macroeconomics very similar across scenarios (classically a smooth growth stabilizing at 1.5%/annum, also see section on boundary conditions).

These limitations also tend to give contrasted importance to the different drivers of change (Le Gallic, Assoumou, & Maïzi, 2017). For example, growth, price of energy, availability of technologies or infrastructure, or public policies, are drivers of energy demand. Most models give a strong importance to growth and technologies in driving energy demand, possibly misleading the reader into thinking that public policies or infrastructure changes are not important, or not possible (see section on energy consumption).

Recommendations for scenario producers:

The modeling choice should be defined and justified (with regards to the driving questions). The following aspects should be reported about:

- Off-the-shelf versus ad hoc model: *has the model been chosen among already existing models or been designed for the future study?*
- Known limitations of the model: *what are the limitations, or possible biases of the model?*
- Adequacy between the model and the driving questions: a justification should be provided about how the model has the ability to answer the driving questions, with regards to its scopes, resolutions/aggregation levels, and limitations. If the model does not have this ability, further analyses should be provided to "fill the gap" (also see recommendations of the section about models).

2. Being transparent about the main drivers of the energy transition in models

Each scenario is described as a consistent story building on model hypotheses and results, but not restricted to them. In this story, the behaviors of some economic agents may be described. This description, even though theoretically partly independent from the model philosophy, is largely driven by it. This is due to the embeddedness of the behaviors of some deciding agents within the model: telling the consistent story which has been modelled is close to telling what rules have been used in the model for decisions by agents.

The philosophy of the model which is used is common to all the scenarios[23] in a study. The most salient feature of energy models, which we call the *model philosophy* lies in what drives the energy mix[24] evolution in the study, and how it does it.

The energy system is influenced by two distinct processes (see Figure 7). 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 distribution system operators (DSOs) and transmission system operators (TSOs), etc.

[23] Except in some specific studies such as (Bovari, Giraud, & Mc Isaac, 2018)

[24] The assets composing the energy system

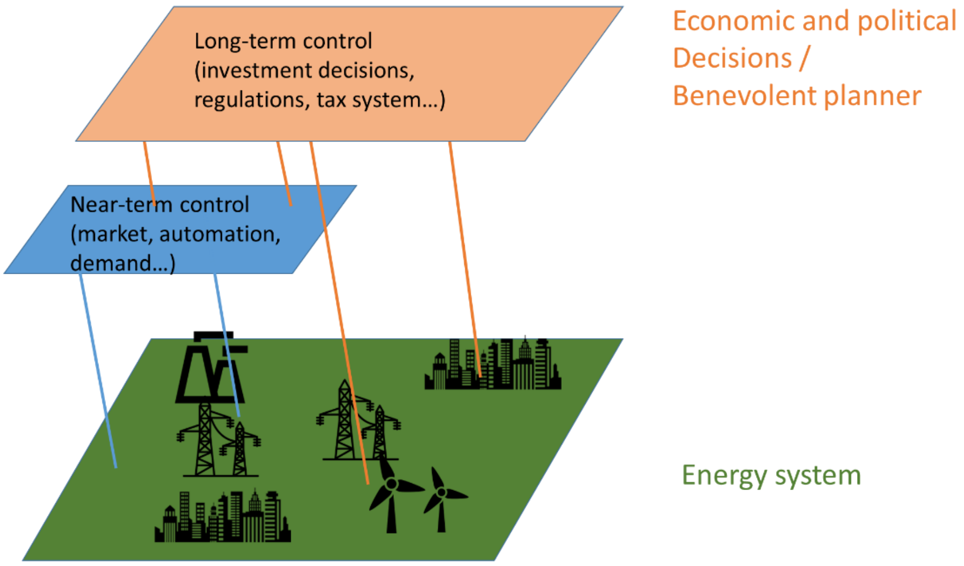

Figure 7 : the energy system is controlled through a long term control process and a near term control process. Future studies use two different ways to model the long term control process: either economic agents decisions are simulated, or a benevolent planner decides.

a. Models simulate agents, a benevolent planner, or both at the same time

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*. In some specific cases, both situations are equivalent: when simulated agents are omniscient, have a perfect foresight and make optimal decisions for their costs, then the situation is the same as if a central omniscient planner was acting to minimize total costs (also called the invisible hand of competitive markets) (Loulou, 2016).

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) (also 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 nature of the deciding agent(s): benevolent planner or simulated agents, should be transparent. For simulated agents, the main ones should be listed. Financers, demand from households, industries…

For more details see the recommendations in the section on models.

D. Highlighting the common points and differences between scenarios

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. Each have a specific storyline defining the consistent overall story through which they unfold. Taken together within a study, scenarios are compared following *study structures*, designed to answer the driving questions. The following subsections explore these aspects on scenarios within a study.

1. Scenarios differ from each other in terms of levers they activate, society objectives they set and uncontrollable uncertainties they explore

Going to the model side is interesting to understand how different scenarios fundamentally differ from each other in studies (see box below).

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? [25]" 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.

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

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 CO_2 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).

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[26] 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.

[26] See (Mark Elsberg, 2017)

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.

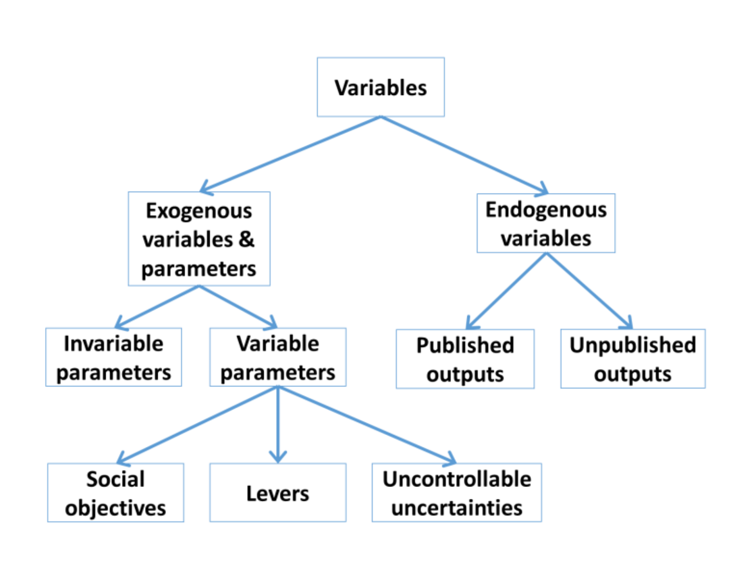

Figure 8: The different categories of variables used by scenarios. Each category is detailed in the following sections.

Recommendations for scenario producers:

The choice of scenarios should be justified with regards to the driving questions (*how have scenarios been designed in the objective of answering 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).

2. Storyline is a dynamic story ensuring the consistency between the hypotheses of a scenario

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.

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 common storyline for all scenarios of the study, completed with specific elements for each scenario

In future studies, some storyline elements are shared among all the proposed scenarios; we call these elements 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 above and Figure 8).

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 box above and Figure 8) 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?*

3. 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), the backcasting 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 approach consists in extending 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 CO_2 emissions are defined, etc), the trajectories to reach it can be computed (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 (no pure backcasting scenario exists). 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 CO_2 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 backcasted 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 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.*

4. Studies select their structures to convey efficiently their 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. Each structure is applied to answer different kinds of driving questions and to convey different messages:

- 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 CO_2 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). Such a story may also highlight the different mechanisms driving the transition. Note however that such comparing a future pathway to the present situation may mislead the reader into thinking that the present situation could actually remain the same in the future, as if time had stopped. Actually immobility is not an option for the future: consider for instance the climate change which would happen if human activities did not evolve at all in the future. The present situation cannot be maintained over the long-term future (Agora Energiewende, 2015; « Costs methodology for 2050 Calculator », 2013).
- 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 of these differences**.

[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
[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

The reference scenario is often considered as a *Business as usual* (BAU) scenario, that is, a scenario in which no society, cultural, economic trend, or any human 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.

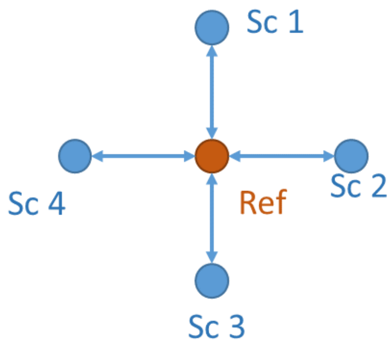

Figure 9 : Illustration of a 4 vs 1 scenario structure, where 4 scenarios are designed from a reference scenario, and are compared to it.

- 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.

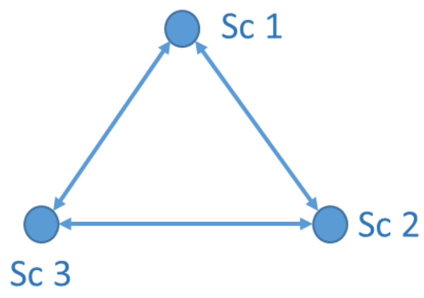

Figure 10 : illustration of a 3 vs 3 scenario structure, where three scenarios are compared with each other.

- 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.

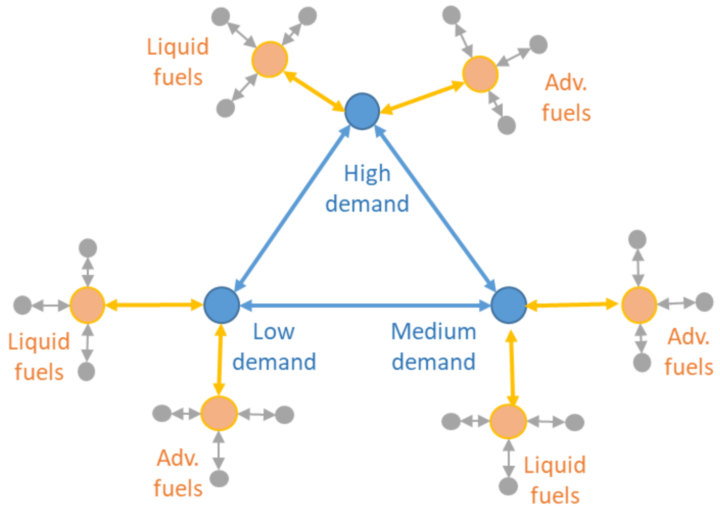

Figure 11: Structure of the (IIASA, 2012) study based on a branching points rationale.

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.

E. Highlighting the risks posed by some courses of actions and the ways to overcome them through discussing uncertainty

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, or parameter, 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 photovoltaic (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.

Expert knowledge on the energy system is required to efficiently choose the exogenous variables and parameters which are both uncertain and which have significant impacts on the end results of scenarios. Indeed, each sensitivity analysis represents extra-modeling time and hence significant extra-costs for scenario producers, and in the meantime it is important to perform all the "useful" sensitivity analyses. **Forgetting a sensitivity analysis handling both a high impact and high uncertainty variable (or parameter) means leaving an important blind spot for the decision maker**, and an easy critique of the study by experts and stakeholders. This expert knowledge can best be gathered through stakeholders and experts consultations about uncertainties and their possible effects (Saltelli & Funtowicz, 2014).

"Global sensitivity analysis" goes beyond expert knowledge by testing all the uncertainties one by one and in various combinations in order to assess the weight of each uncertainty in the final results (Saltelli & Funtowicz, 2014).

However, this method requires large computation capacity and/or an (extremely) long time. An alternative method for studies with social objectives (backcasted components) is to perform a robust optimization computation: it means directly finding the pathways which respect the social objectives for all the possible uncertainties (including the worst cases) (Nicolas, 2016).

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 in terms of 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?

Also, apparently small variations of hypotheses about key characteristics of power supply technologies may lead to large variations in final power mixes. This may happen in models based on least-cost optimization, when marginal costs between two technologies swap due to the small variation in some characteristics (Nicolas, 2016).

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.

Typically, depending on the selected model and hence on the boundary conditions, the following variables and parameters can be tested for sensitivity analyses: power demand level, costs and characteristics of key technologies, delay in key actions, discount rates, desirability from society of the proposed actions, power demand flexibility,

c. As any other scenario, a sensitivity analysis has to be 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. They are also useful to better inform decision-makers about the possible risks society would face if it engages in such or such action, in turn fostering the adaptation to these risks.

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]. Justification should be provided about the fact that all key uncertainties are handled.
- Qualitative or quantitative nature of the analysis. Qualitative analyzes are useful for scenario community building and for risk assessment by decision-makers. 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

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

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?*

3. Resilience may be a useful concept for future studies but it should be precisely defined before being studied

As described by (Juffé, 2013), resilience may appear as a quite fuzzy and overused term, applying to several fields (mechanics, psychology, ecosystems, city planning, policy making…).

Originally, the term comes from the field of mechanics and describes the resistance of a material to a shock: does it break or not? Resilience tests take part of a set of tests which aim at describing the reaction of a material to different mechanical constraints.

Then the term has then been used in the psychology field to describe the ability of a person to recover after a psychological trauma (such as a war experience, a business failure…). The term has also been used to describe the reaction of ecosystems to human activities (Dron, 2013).

Now the term can be found in various fields linked to climate change physical risks, natural disasters, finance... It describes the ability of a system to "properly react" in case of a shock.

However, human systems to which this term seemingly applies (e.g. city resilience) are actually composed of various sets of systems such as, for a city, the buildings, but also the networks (energy, water, roads, rails, waste removal…), the human systems (companies, associations, local governance, religion communities…) and so on. Hence, what must resist to the shock, that is, what remains functional after the shock, should be precisely defined: **resilience of what?**

Also, the precise objective of the resilience has to be provided: what is considered as unacceptable after the shock, and what is acceptable? In other words, what is the unacceptable functionality loss of the considered system after the shock? These questions can be summed up as: **resilience for what?**

Finally, the shocks that these humans systems can undergo are extremely various: natural disasters (earthquakes, tornados, floods, droughts…), network failures (power outage, water network problems…), exterior human actions (terrorist attacks, economic war…), internal human systems failures (financial crisis) and so on. Hence the question: **"resilience to what?"** is key.

If scenario producers want to explore the resilience of different systems in their pathways, they need to ask those three questions.

- Resilience of what? Here, scenario producers need to define the systems they deem important to maintain. For example, resilience of the power system may be studied.
- Resilience for what? How should the defined systems resist to shocks? Here scenario producers must define what reaction to a shock seems acceptable and what seem unacceptable for them. For example, scenario producers may deem that the power system must ensure the proper operation of vital services such as

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

health facilities, drinking water network, and food logistics (for example, cooling processes to maintain the cold chain)

- These choices are subjective and depend on the geographical perimeter. Transition stakeholders and citizens can be involved in the process of making these choices.
- Resilience to what? Here scenario producers should define what events they want the system to be resilient to. This choice depends on the probability of different events to happen in the considered geographical perimeter and timeframe, their possible magnitude and effects. For example, scenario producers may choose to study such events as a severe drought impacting hydropower plants and the cooling of thermal plants, or a long winter period with no wind nor sun impacting PV and wind turbines power production.

The answers to these questions define "stress tests", that is, events which scenario producers imagine and for which they describe how the selected systems react. One major difficulty for scenario producers is that they describe pathways as opposed to steady states. Hence the following question must be asked: resilience at what time? The moment at which the adverse event happens during the proposed transition may radically change the reaction of the considered systems: does it happen after the transition is completed? Or at the middle of it? Or at the moment the considered system is the weakest with regards to the adverse event?

Note that these stress tests may not be runnable with the models traditionally used to produce scenarios, as they model a world in which no shock happens (in all the scenarios we reviewed[34], even BAU scenarios with large GHG emissions, everything goes fine). Models could be designed to run stress tests. However it would be highly difficult, if not impossible, to calibrate these models as they would have to simulate situations which did not happen yet, or very rarely. Most probably, scenario producers willing to tackle resilience would rather imagine qualitative narratives and describe them in a concrete way.

Recommendations to scenario producers

Scenario producers should make their strategy about resilience study and about stress tests explicit: is this topic covered?

They should define what they call resilience by answering the four questions: resilience of what, resilience for what, resilience to what and resilience at what moment. In this process, they should report who they consulted (what stakeholder, expert, citizen…).

Having defined all these aspects they include in resilience, scenario producers should provide the associated narratives. The stress tests should be applied to all pathways in order to compare the reactions of the considered systems between the pathways.

[34] Except scenarios in (Bovari et al., 2018)

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

In this guidebook, *published outputs* are the endogenous variables extracted from model runs. The *results* of future studies are one or several stories about the energy system evolution and the associated co-evolutions of surrounding systems. Each scenario leads to a story, and stories are compared to each other within the study report. In other words, the results of a future study are based on published outputs but also on hypotheses of each scenario. Published outputs and hypotheses are mixed into a consistent story about the future.

In this section we develop about the choice of what to publish and how.

A. The crucial and subjective choice of which narrative elements 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) as well as the exogenous variables (those feeding 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 CO_2 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 outputs* (see Figure 8). Some exogenous variables and parameters can also be judged important to communicate. For example the share of RES in the power system, CO_2 emissions, land use, GDP evolution, lifestyles evolutions, policy evolutions or employment evolutions might be deemed important to communicate and hence published into consistent stories. All these variables are used to produce *narrative elements* feeding the whole story.

Narrative elements can be extremely various in their natures. They are the description of aspects of systems included in the future study sector scope (see Figure 1). Hence they can relate to a 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 CO_2 emissions, or lithium depletion).

In other words, narrative elements can be of two types: elements 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 elements about the evolution of the *surrounding systems*.

B. Considering the number of significant figures to publish in narrative elements

Future studies usually quantify some processes and evolutions happening in the core, or surrounding systems. When these processes and evolutions are described in the report, numbers are used, with more or less significant figures.

Given the high uncertainty of hypotheses and the high uncertainty of parameters represented in the model between modelled entities over long time horizons, we could expect the number of significant figures to be low.

Numbers per se are meaningless for decision-making until they are compared (to the current situation, or to another scenario…). The risk of keeping too many significant figures is to wrongly conclude that two situations are significantly different and to favor one of them, whereas the uncertainty on these situations makes them fundamentally non-differentiable. The NUSAP methodology about data publication prevents such wrong comparisons to happen by providing the spread for each number which is published.

The complexity of providing such spreads is as high as the complexity of the model used. Indeed, the task consists in evaluating the spread of each parameter within the model and check how these spreads propagate in the model and how they finally impact the spread of published variables.

In doing so, key hypotheses (exogenous variables which distinguish the scenarios) must be considered as certain (that is, their spread must be zero). Indeed, the scenario approach of future studies is already a way to tackle the uncertainty of these hypotheses by studying the consequences of several of them: these hypotheses are the "if" in the "what… if" question that scenarios seek to answer. On the contrary, model parameters (such as the unitary amount of GHG emitted by the various considered processes, the elasticity coefficients used for simulating consumption behaviors, the characteristics of the various production plants at start year and so on) are by nature uncertain and should come with an uncertainty range.

No future study within our scope discusses the uncertainty range of its outputs. Their implicit assumption is that the current energy system and its operation is perfectly known.

C. Impact assessment best serves as a narrative about the interactions between the energy transition and the surrounding systems

While the first category of narrative elements (about the evolution of the core system) is considered as the description of the energy system (or power system) transition, the second category (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 CO_2 emission, but that CO_2 emissions have no impact on the energy transition. This is a simplification of reality as CO_2 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 use the terms *impacts* and *interactions with surrounding systems* interchangeably. 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).

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

The choice of which narrative element 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 core system.

The evolution of surrounding systems such as the environment, ways of lives, or the economy highly interests citizens, households, and various economic agents and policy makers, whereas the evolution of the technical energy system per se mainly 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 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, even though some debate may happen about the core system (such as debates between technologies). However, oftentimes these debates are linked to particular interests. Given the general interest stance of our framework, **we consider that no specific core system can be judged per se: it can only be judged through the various interactions it has with surrounding systems, including society**. 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[35] and human resources to produce future studies. The lower this capacity and resource amount, the lower the number of interactions which can be studied.

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 tackle climate change 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.

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

It is now commonly acknowledged that extended cost, as a single value (a scalar value), cannot be a proxy for all the aspects of an energy transition (also see section on economic evaluation). Prices (shaping up overall costs of a transition) do not include externalities (by definition of an externality: an impact which is not taken into account by economic decision makers, e.g. unregulated pollution). Some studies integrate externalities (typically through a carbon value) in an extended cost indicator to compare their scenarios. For example, (Agora Energiewende, 2017; Fraunhofer ISE, 2015) integrate a carbon price in their results. 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).

In our framework, we value transparency and concreteness of descriptions. Aggregating indicators representing different natures of quantities into a single indicator leads to less transparency and less concreteness.

Furthermore, it is conceptually and practically impossible to aggregate all the externalities into a single indicator. As studies go towards studying more and more impacts on surrounding systems (biosphere, lifestyles, material resources…), extended cost indicators should be abandoned.

- The list of all externalities (positive or negative) is not known and cannot be completely known, as many externalities can be detected only at the local scale (local climate change due to vegetation changes, local water cycle modified or polluted…). Hence knowing, and computing all the externalities would require the proposed transitions to be defined at a very high space and time resolution.
- 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 compute a monetary value assigned to the different elements of biosphere, for properly informing the choices between possible

[35] 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.

transitions. Biosphere is an extremely complex system which might never be sufficiently understood conceptually speaking (knowledge that we do not know yet of a significant number of species, lack of knowledge about the species we know exist, lack of knowledge about the complex interactions between known and unknown 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 transitions.

Given these two deep uncertainties (one due to a practically impossible to reach resolution in transition description, the other due to the radical complexity of the systems which are studied), we conclude that **some aspects of the transition would be described under a monetary value only with an arbitrarily high uncertainty**. Hence using such values would be harmful for the energy transition debate as the debate would rather focus on the legitimacy of the people who chose the values, than on the transition itself.

Instead, we consider that narrative elements on 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 (supported by the associated key indicators if any) are much more efficiently communicated separately and synthesized through a multi-criteria dashboard (as illustrated in II.E.), 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.

The narrative about "pure" monetary costs (with no integration of externalities) must be kept as it is very useful to think such aspects as how much human work will be required to perform the transition, when it will be required, the skill-level of the different works needed for the transition, the possible impacts on trade with neighbor regions and so on.

The narratives about impacts on surrounding systems actually depict the various consequences of that human work on society, employment, the economy and the environment.

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.

F. Descriptions of impacts should be concrete enough to detect acceptability issues with stakeholders

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

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 energy transition debate for all transition stakeholders (companies, citizens, employees, political and business decision-makers…)., a pre-requisite for democratic decision-making.

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 (see I.G.1.b).

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 scenarios in which the impact goes beyond acceptable bounds are clearly described as such (Schubert et al., 2015). Typically, CO_2 emissions are assumed beforehand to decrease below a given level in transformational scenarios, whereas acceptability issues are generally assessed ex-post.

Recommendations to scenario producers

Scenario producers should detail their strategy about results publication, especially interactions with surrounding systems, and should justify this strategy with regards to the driving questions, to modeling constraints, to ethical considerations, etc.

Specifically, the list of the published outputs should 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.

In other words, the following aspects should be considered:

- Nature of the published outputs and interactions with surrounding systems 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 of including this aspect in their scenarios (including the reference/BAU scenario, if any).

Scenario producers should detail and justify their transparency strategy on the spread of the quantified elements they publish. When comparisons between such elements are performed to draw conclusions, considerations on the significance of their quantitative difference should be provided.

Scenario producers should detail their strategy on description concreteness, including the aspects they specifically want to describe concretely and those they do not (either within the core system, or among its interactions with surrounding systems: climate, resources, economy, ways of lives and so on), the target audience of these descriptions; and the means involved in that objective (how stakeholders have been involved in the study process).

G. 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.

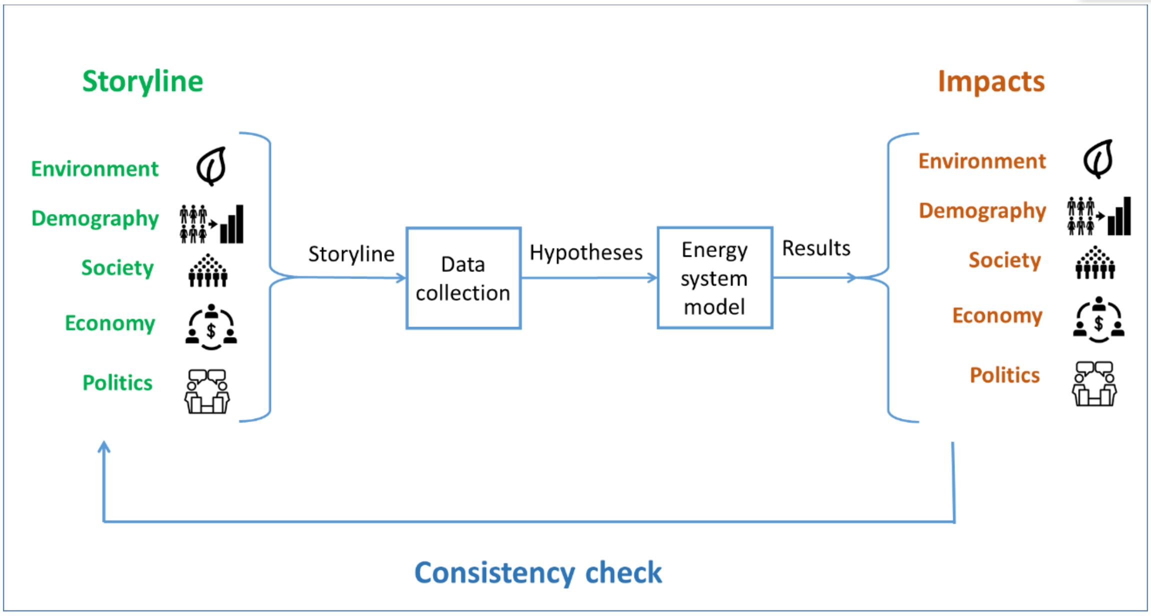

Figure 12: The storyline is at the origin of the input variables which feed the model, producing in turn results and insight about the various consequences of the initial storyline. As long as there is no modeled feedback between these impacts and the energy system, a manual check has to be performed that the impacts are not inconsistent with the initial storyline.

Another example is typically found in Reference, or so-called Business As Usual 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. This is not necessarily a problem if the inconsistencies are explicitly stated and interpreted. However, most inconsistent scenarios are presented as if they were consistent.

Secretly inconsistent scenarios (that is, scenarios which are inconsistent without being clear about it) may harm decision-making process by hiding important information. On the contrary, 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.

An inconsistency can also be avoided by endogenizing the feedback loop at its origin within the model (see section on boundary conditions).

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?*).

H. Synthesizing results through a study dashboard

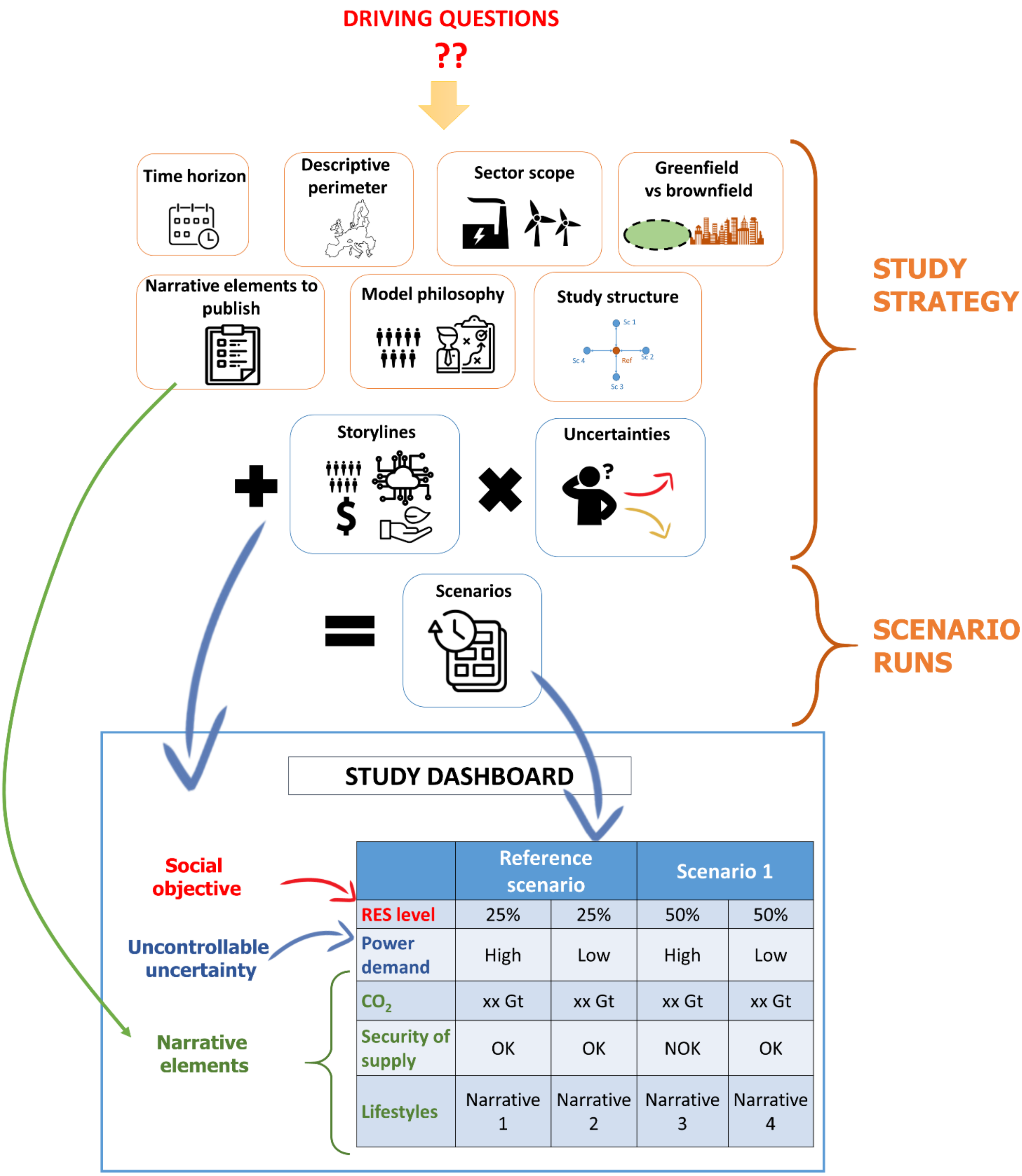

Figure 13 : The study strategy steps and how the main study dashboard is defined from them. The presented social objectives, uncontrollable uncertainty and narrative elements are for illustration purpose.

The study dashboard compares the different scenarios along different narrative elements.

The different scenarios are distinguished through the different social objectives, levers they activate and uncontrollable uncertainties (sensitivity analyses) they put into play.

Both the scenarios and the nature of the narrative elements derive from the driving questions, as described in the previous sections. These narrative elements are produced from (a) the variable parameters which differentiate the scenarios (levers, social objectives and uncontrollable uncertainties) and (b) the published outputs, which are the endogenous variables that the study producer deem useful to compare between scenarios.

Hence this dashboard is naturally derived from the study strategy steps.

Recommendations to scenario producers

Scenario producers may use a synthetic study dashboard to highlight their results in a simple and efficient way. The structure of the dashboard may be defined as described in this section.

I. Deriving conclusions and recommandations from results

As argued in the transparency framework for energy transition studies by Cao et al (Cao et al., 2016), "the conclusions of a study represent, in contrast to the model outputs, the outcome of the whole modeling framework." In other words, model outputs are interpreted and post-processed (for example to highlight the pros and cons of the different scenarios by comparing the different scenarios), generating the final results published in the report. From these results, qualitative and quantitative conclusions are drawn, usually leading to recommendations "intended to give some kind of advice to decision-makers."

Scenario producers and scenario users interviewed in that study raised a major critique on energy transition studies, about the **lack of traceability between the results and the conclusions or recommendations**. The recommendations may be perceived as untraceable, or even arbitrary, if they are not directly related to the results of the study. Further than the link between the output of the model and the conclusions, the goal of a future study is to tell concrete and internally consistent stories (no matter if some elements of these stories are "outputs" or "inputs" of a model, or not even related to a model), and logically draw conclusions from these stories. In other words, when a model is used, the links implemented in it should be told as stories' elements when the conclusions are drawn.

Most of the studies we reviewed show an explicit link between their technical results (outputs of their models) and the conclusions they draw. A few do not, in which case the reader may think the conclusions have been decided by the study contractor before performing the study, mostly reflecting its particular interests and/or values.

Among the studies which link the conclusions to their results, the following shortcomings can be noticed:

- The reasons why these results have been obtained, given the model and the input hypotheses, are not provided. In other words, it is not clear why such results have been obtained from the hypotheses (also see section on Models and I.2). In this case the reader is supposed to blindly believe what the model simulates.
- Recommendations only indicate the direction which should be taken to follow the described pathway, with no qualification of the amount of effort which would be required. In this case, the described pathway may be looked at by the reader as pure wishful thinking as nothing indicates the pathway is realistic.
- The conclusions are too formal compared to what the results actually show. For example, a study may conclude that the development of PV capacity is *required* by investigating a scenario with PV compared to a reference scenario. To show that PV development is required would need to show that there is no alternative, hence investigating many other scenarios.

Recommendations to scenario producers

Scenario producers should describe the causal chain captured by their model as well as provide an analysis to support their recommendations, "thereby highlighting the process by which the results-recommendation relationship is created" (Cao et al., 2016). In other words, conclusions and recommendations should be logically derived from the scenarios.

Conclusions should be written with precision and sufficient hue to reflect the actual results.

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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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