EXPLORING FUTURES TO PLAN ENERGY TRANSITION

GUIDELINES
FOR FUTURE STUDIES ON ENERGY AND POWER TRANSITIONS

Synthesis Report
of the study led by Nicolas Raillard
for *The Shift Project*

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THE SHIFT PROJECT
THE CARBON TRANSITION THINK TANK

Foreword

The Shift Project is a French think tank that advocates the shift to a post-carbon economy. As a non-profit organization committed to serving the general interest through scientific objectivity, we are dedicated to informing and influencing the debate on energy transition in Europe.

Many other actors (NGOs, public actors, professional associations, international organizations) seek to inform and influence the debate on energy transition through future studies. Several future studies reports are published each year in the form of "grey literature". These reports are not peer reviewed per se, but they involve professional or academic experts from various fields in their constructions, and they inevitably trigger reactions and criticism when they are released (a form of post publication peer reviewing).

In January 2018, *The Shift Project* launched a project whose goal is to **foster the development of a science-based debate on energy transition through the scenario approach**. Energy transition is a long-term process taking place through time, and involving all sectors of the economy, the environment and of society. The scenario approach clearly meets the requirements for exploring energy transitions: it is holistic and time-based. In addition, it leaves room for creativity and for exploring new, unconventional pathways. However, for this approach to positively influence the public debate on energy transition, it must be compatible with physics, and it must be truly holistic (otherwise certain first order consequences of the proposed transitions could be neglected).

In this effort, *The Shift Project* asked Nicolas Raillard to conduct a collective work aimed at producing a set of guidelines dedicated to future studies, in order to foster transparency and help them overcome their first-order limitations.

The main results of this work are the guidelines contained in the complete Framework (12 Technical Files). These guidelines are primarily addressed to scenario producers. The present Synthesis Report and its Executive Summary are also addressed to all actors of society interested in gaining knowledge from, and about, future studies on energy transition.

Comments from scenario producers

« The Framework developed by The Shift Project is a very useful compass to navigate into the jungle of energy transition scenarios. This Framework helps scenario producers provide greater transparency and communicate in a collectively more efficient way, leading to greater ease of comparability between their respective scenarios. Ultimately, this tool carries the public debate on energy transition beyond pure expert discussions. »

Dimitri Pescia
Senior Associate at Agora Energiewende

« This new report by The Shift Project highlights the practices, limitations and needs of scenario production on power systems within energy transition, in a very clear and documented way. An essential report for improving the understanding of energy transition scenarios by stakeholders, this report is also useful for scenario producers to improve their craft. »

Emmanuel Hache
Economist at IFP Energies nouvelles (IFPEN)

« The Framework proposed by The Shift Project rightly insists on what I consider as three essential points for the debate on energy transition:

- *The energy transition is a long-term process. As such it requires to tackle ongoing changes from various sectors and points of view, with great transparency with regard to the selected objectives and scenarios; the use of interviews and of expertise from various fields (including academic expertise) improves the exploration of possible futures and fosters the debate for public decision-making.*
- *The energy transition is characterized by high uncertainties on future technology pathways and on possible society changes. Hence rigorous modeling is required to highlight the inner-consistency or contradictions of explored futures.*
- *Environmental aspects in the largest sense (global warming, resource exhaustion, biodiversity disappearance) drive the exploration of scenarios; public decisions must be based on a very large and exhaustive socio-economic assessment of the described futures, including all activity sectors. »*

Jacques Percebois
Professor Emeritus at University of Montpellier
Head of the Centre de Recherche en Économie et Droit de l'Énergie (CREDEN)

« This work highlights the needs for scenarios to be more transparent, more concrete and tangible in the way they describe transitions. Thus they could reveal intelligible elements to all actors so as to enable them to understand where they stand in the described transitions. »

Yann Briand
Climate change and Transport esearcher at IDDRI
Contributor to the Deep Decarbonization Pathways Project (DDPP)

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Acronyms and units

Acronyms

AC	Alternative Current
BAU	Business as usual
CAPEX	Capital expenditure
CCS	Carbon Capture and Storage
CH_4	Methane
CHP	Combined heat and power
CNG	Compressed natural gas
CO_2	Carbon dioxyde
CSP	Concentrated Solar Power
DC	Direct Current
DSO	Distribution system operator
ENTSO-E	European Network of Transmission System Operators for Electricity
EROI	Energy return on invested
ES	Energy System
ETS	Emissions Trading System
EU	European Union
EV	Electric vehicle
FCR	Frequency Containment Reserve
FRT	Fault ride through
GDP	Gross Domestic Product
GHG	Greenhouse gas
H_2	Dihydrogen
IAM	Integrated assessment model
ICE	Internal combustion engine
ICT	Information and communication technologies
i-LCOE	Investor LCOE
IO	Input-Output
LCOE	Levelized Cost of Electricity (Energy)
LNG	Liquified natural gas
LULUCF	Land use, land use change and forestry
N_2O	Nitrous oxyde
NGO	Non-governmental organization
NIMBY	Not in my backyard
OPEX	Operational expenditure
PS	Power System
PV	Photovoltaic
R&D	Research and development
RES	Renewable energy sources
s-LCOE	System-wide LCOE
SM	Synchronous machine
TF	Technical file
TOE	Technical and organizational efficiency
TSO	Transmission system operator
TYNDP	Ten Years Network Development Plan

UK	United Kingdom
VRES	Variable Renewable Energy Sources
VSM	Virtual synchronous machine
WACC	Weighted Average Cost of Capital
WEO	World Energy Outlook

Units

A	Ampère
Hz	Hertz
V	Volt
W	Watt
Wh	Watt-hour

k	kilo (x 10^3)
M	Mega (x 10^6)
G	Giga (x 10^9)
T	Tera (x 10^{12})

I. Introduction

Energy transition is becoming the focus of attention of a growing number of actors: companies, citizens, NGOs, the media and decision-makers. The associated challenge of achieving a successful energy transition is huge: for the first time in history, a necessary transition concerns virtually all the sectors of the economy and every aspect of our daily lives, at the global scale. Severe, global consequences are expected if energy transition (or its absence) fails to significantly and rapidly reduce the pace at which we emit greenhouse gases (GHGs). Adverse consequences may also be expected for actors who depend on fossil fuels but do not foresee their dependence strategically, should these fuels become critical due to geological or geopolitical reasons.

A. Future studies are vital tools for our societies to discuss and plan our common energy future

Energy transition is a long-term process taking place through time, and involving all sectors of the economy, the environment and society. Future studies aim at exploring questions about the future. Within future studies, some use a scenario approach, that is, they imagine and describe scenarios about the future in order to explore their implications for different actors. The scenario approach clearly meets the requirements for exploring energy transitions: it is holistic and time-based. In addition, it leaves room for creativity and for exploring new, unconventional pathways which might prove useful for asking new questions and finding out-of-the-box solutions for this first-and-last-of-its-kind challenge.

Hence, future studies on energy transition are vital tools as they enable actors of our societies to discuss, share, and envision different futures for better planning. In some of these futures, our societies fail to achieve the transition, and in some others they succeed. It is crucial that this type of planning tools becomes widely used. The more future studies, the more useful information we will obtain on energy transition, and, hopefully, the better our society-wide decisions will be.

B. They tackle a highly complex and deeply uncertain subject: energy transition

However, their subject (the evolution of the energy system) is highly complex. The energy system is complex per se, involving a great number of production entities (companies, production facilities, etc.) and consuming entities (final consumers, consuming appliances and equipment, etc.), through distribution networks. The energy system is totally intertwined in our daily lives, in all the sectors of our economies, and directly interacts with the environment through resource extraction, pollution, emissions, land use, water use, and so on.

Their subject is also deeply uncertain due to their long-term nature. Energy system infrastructures have different life durations, from several years for consuming appliances to several decades for large production facilities (refineries, power plants, and so forth) and networks (power grids, roads, service-station networks, etc.). The further the time horizon of future studies, the greater the number of possible evolutions.

The task of future studies is vital but extremely difficult to achieve.

C. Are there too few resources dedicated to future studies?

Fortunately, several future studies on energy transition are produced every year. They are produced by NGOs (WWF, Greenpeace, Association négaWatt, Öko-Institut, Réseau Action Climat), think tanks (Agora Energiewende, *The Shift Project*, IDDRI), research institutes and organizations (ANCRE, Fraunhofer ISE), public agencies (ADEME), academies, public institutions (European Commission, national ministries), foundations (European Climate Foundation), international institutions (IEA, IIASA, IRENA), professional associations (SFEN), and grid operators entrusted by the law with responsibilities to publish adequacy and prospective studies (RTE, ENTSO-E).

Many actors produce future studies, but the amount of resources and the time spent on developing future studies may seem insufficient with regard to the stakes. During the national debate on energy transition in France (2014), 11 national scenarios were reviewed. The number of people involved in these scenarios ranged from a few to several tens of people. Most probably, not even 500 people worked on producing these scenarios that were used to plan certain aspects of the long-term future of French society, several hundred times less than the number of people involved in car production in France (about 150,000 people).

More resources could be dedicated to developing computational tools, collecting data, popularizing and communicating results, as well as discussing, validating, documenting, sharing and debating these tools, data and results.

D. The current collective limitations of future studies

1. They are insufficiently transparent to tackle complexity and uncertainty

Future studies **explore different questions about energy transition**. Their timeframes usually range from 15 to 50 years ahead (with time horizons between 2035 and 2070). Their geographical scopes are various: the world, the European Union, or individual countries. They explore different aspects of energy transition: costs, climate impacts, other environmental impacts, employment, etc. They each produce a number of scenarios, which are compared to each other with different methods and indicators.

They are **based on complex models** which represent the energy system, or some parts of it (e.g. the power system) in a (necessarily) simplified way. Most of these models are not open to the public, and/or not properly documented for a layperson to understand their mechanisms.

Future studies are usually published under the form of reports, sometimes under the form of academic papers. The study reports synthesize the hypotheses and the results for the different scenarios and provide a few explanations on the model. They then report different narratives for the scenarios, and compare these narratives to draw conclusions on energy transition, and sometimes to provide explicit recommendations to policy-makers.

However, the transitions described are so complex that the **reports necessarily have to filter information, select the information deemed useful and important, and organize it so as to build a story out of it**. These steps are usually not documented or peer-reviewed in the academic sense. The uncertainty regarding the long-term future is so great future studies cannot handle all of the possible futures, and cannot document the reasons why they have not explored all the other possible futures.

Future studies are tools used to discuss a topic involving the future of all the actors of society. **They are explorations of highly complex and deeply uncertain topics, hence they have not yet achieved a satisfactory level of transparency.** The very subject of these future studies place them in the spotlight and thus attract criticism.

At each publication, readers find doubtful hypotheses, blind spots, or misinterpretations of the results. For example, readers may find that cost hypotheses for a technology have been too optimistic; that the development of a technology has been limited for no relevant reason; that performance hypotheses for a technology are too low; that a technology has been assumed mature prematurely; that a significant cost item has been forgotten in the global cost assessment; that the geological availability of a material should have been checked; that the energy accounting in the scenario is wrong; that fuel price hypotheses are absurdly stable; that GDP should not be set as a hypothesis but instead computed as a result; that the employment assessment is biased by considering only a few sectors of the economy; that the economic theory behind the model is not credible; that the transition described would not be accepted by people; that the proposed electricity system would not function properly during cloudy winters; and so on.

2. They do not play collectively enough

Furthermore, when policy-makers want to base their decisions on future studies, they have great difficulties in making the studies dialogue in a constructive way. In 2014 in France, during the national debate on energy transition, decision makers (Ministry of the Environment) ordered a pedagogic report on the various scenarios that had been published in recent years (Grandjean, Blanchet, & Finidori, 2014). This report attempted to simply sum up the different scenarios and compare them as a function of a few key indicators. The team in charge was able to meet the scenario producers in order to obtain unpublished data from them and perform the comparisons. In other words, **comparing published scenarios is not an easy task because future studies use different methods, different indicators and different scopes.** The reason is that the questions they seek to answer and their target audience are different.

E. Our objectives

Given that future studies are a key tool for collectively discussing and debating the long-term planning of our societies, and given the difficulties they meet to inform public debate, *The Shift Project* decided to produce and propose a methodological Framework addressed to scenario producers. In this Framework, guidelines would be provided to help future studies be transparent regarding the key aspects of energy transition on which they may be criticized, and to propose tools to collectively think of these aspects more efficiently (by providing more efficient vocabulary and standardized ways of presenting the information future studies contain).

In this context, we set for our project the following objectives:

1. Produce a list of key topics for describing energy transition in future studies

Our first objective was to establish a list of key topics for describing energy transition in future studies. This list should contain all the elements that need to be discussed when thinking energy transition, that is, all **the elements which may totally change the outcome of a scenario if they are integrated in the discussion rather than being absent from it**. We also wanted to **understand what the scientific community has to say about these topics**.

2. Understand the collective practices for scenario production

Our second objective was to understand the practices of the scenario community (all the actors involved in future study production) when it comes to scenario production and reporting, based on publicly available information (future studies reports and annexes, models documentations).

We limited our efforts to the **future studies which are public, large-scale (at least national), long-term, and which shed a particular light on the power system**. The reasons for this choice are two-fold: the power system is largely described as gaining importance in the long-term in many scenarios, through the electrification of uses; we could not envisage studying the whole energy system in our project, because we had a limited amount of resources to perform it. Hence this project may be completed by specific analyses of the other energy carriers.

3. Critically analyze these practices

Our third objective was to **analyze practices in order to highlight the collective limitations of future studies.**

In our Framework, the limitations of future studies are defined with regard to the essential goal of future studies: informing the society-wide energy transition debate. In our view, pertinent information for the debate **must be scientifically based**, **transparent**, and **intelligible for all the interested stakeholders**.

We assessed the level of importance of these limitations with regard to their degree of influence on the conclusions drawn on energy transition.

4. Propose guidelines addressed to scenario producers

Our last objective was to provide guidelines addressed to scenario producers in order to **overcome these limitations at best, or to make them transparent** at least, to inform the public debate as well as possible.

F. Our approach

To achieve these objectives, we set up a project whose main milestones are illustrated in Figure 1.

We started the project by gathering a team of approximately 10 experts from the energy sector (industry, academic bodies, associations), some of whom have worked or are still working on future studies projects. The goal of this launching group was to establish an initial first list of important topics for discussing energy transition.

In the second phase, we consolidated this list by conducting around 20 interviews with experts from the energy sectors and from the scenario community. In parallel, we reviewed the academic literature and grey literature associated with these topics, including future studies, to synthesize it. From this work, we were able to obtain science-based recommendations for future studies. We compiled technical files containing, for each key topic, information about the topic obtained from the literature review, and the associated recommendations.

In the third phase, we organized a set of workshops with around 20 experts to review and discuss the list and the requirements we obtained for the different key topics. We then integrated their feedback in the technical files and performed more literature reviews to obtain a consolidated overview of the key topics for energy transition.

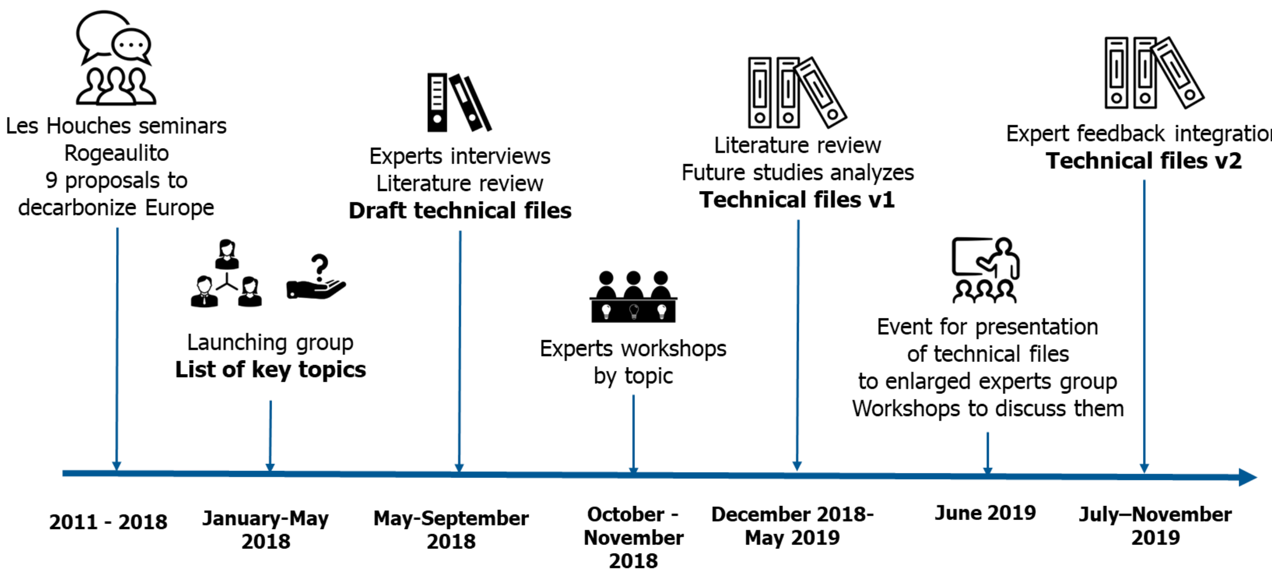

Figure 1: Project timeline and milestones.

For most of the key topics, we reviewed the practices used in a set of future studies to obtain an overview of current collective practices. We included approximately 20 future studies in this review. However, it was not systematic: each study was not fully screened for all the key topics. Rather, for each topic a few studies have been selected and analyzed.

We enriched our technical files with these practices, and presented them at a dedicated event for an enlarged circle of experts, in which different workshops were set up to discuss them. About 60 experts participated in these workshops. We finally consolidated the technical files with the feedback from the workshops.

The present synthesis describes the final version of the Framework obtained as the result of these steps.

The **Framework contains 12 different technical files**, tackling more than **120 key topics** and providing associated recommendations to scenario producers.

The whole output is based on a **bibliography containing more than 300 works and 20 future studies**. We estimate that the **experts dedicated a total of more than 200 hours of their time** for this project.

II. Overview of the Framework

The Framework is composed of 12 technical files (TF) covering different aspects of the description of energy transition by future studies, as described in Table 1.

All these aspects interact together because they are linked to different aspects of the energy system, as described in Figure 2. This is why we have made many cross-references within technical files.

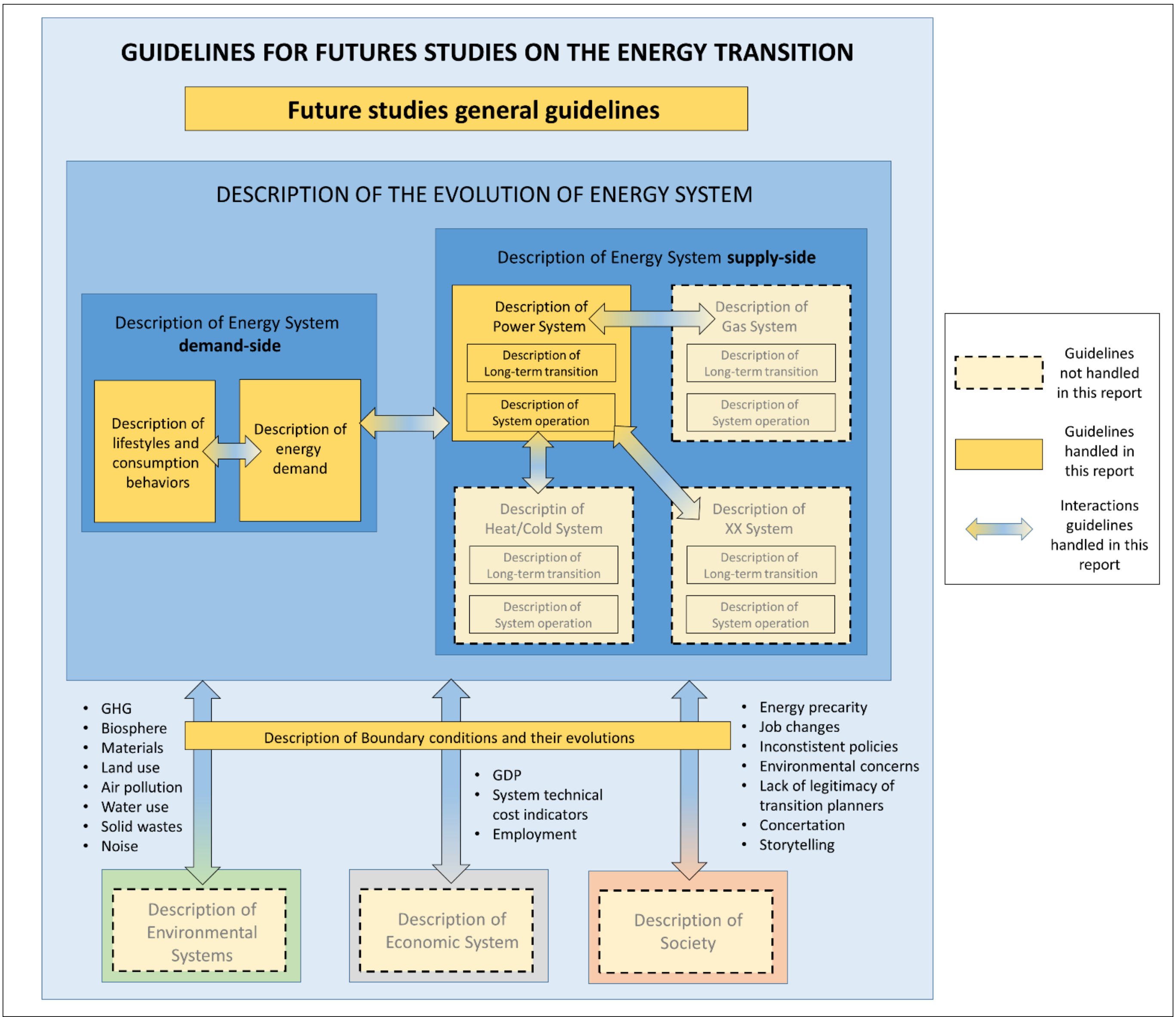

Figure 2: Graphical representation of our Framework. Double-arrows and deep yellow boxes are handled in our Framework. Boxes represent different systems, including the energy system and systems surrounding it (environment, economy and society). Double-arrows represent interactions between systems.

The whole methodological Framework can be found on *The Shift Project*'s website:

https://theshiftproject.org/en/home/

#	**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

Table 1: List of the Technical files composing the methodological Framework.

Technical file#1 handles general considerations on future studies, their goals, how they are framed and produced. Technical file#2 complements this file by discussing aspects of models used by future studies, and their transparency.

Technical file#3 introduces the translation of the storyline into quantitative data to feed the model used. These data are called the boundary conditions and represent preset interactions with surrounding systems, which drive and/or constrain the evolution of the energy system.

On the demand-side of the energy system, technical file#4 deals with the evolution of energy consumption while technical file#5 handles the link between policies and consumption behaviors.

On the supply-side, we limit our framework to the power system. Technical file#6 deals with the long-term transition of the power system, while technical file#7 deals with its near-term operation.

Technical file#8 is an introductory section for technical files#9 to #12. It focuses on the general question of impact assessments in future studies. Technical file#9 provides guidelines about the description of transition desirability in scenarios; technical file#10 provides guidelines on the description of environmental impacts; technical file#11 provides a framework to discuss and describe economic evolutions in scenarios; technical file#12 provides guidelines about the description of the evolution of employment.

The different technical files are summarized in the next section.

Recommendations are highlighted in blue.

New concepts to efficiently discuss and describe energy transition are in *italics*.

III. Summary of the Technical files composing the Framework

A. TF#1: Future studies on energy transition

This section of our Framework addresses the general subject of future studies exploring energy transition issues.

After their publications, future studies are often the object of many reactions and criticism from different actors, such as actors working in the energy sector, environmental NGOs, interested citizens, policy makers and economic decision-makers in the energy and environment sectors. **Our Framework covers future studies that address policy-makers and the general public.** Our scope **specifically focuses on future studies that explore in detail the long-term transition of the power system and its operation**.

Future studies are tools used to inform the debate on energy transition, by answering questions about the evolution of the energy system, a highly complex system whose long-term evolution is deeply uncertain. They are intended by their producers to be technical, science-based objects and are largely perceived as such.

However, **future studies are also political objects, as they primarily seek to influence a target political debate or decision-making process.** Future studies embed different **ideologies and interests** that are sometimes lost in the complexity of computational models representing large sectors of the economy and of society. For example, different ways to envision how human beings behave and how they will behave in the future are embedded in different scenarios, sometimes with no clear description of these behaviors.

This should not be seen as a problem, inasmuch as this influence and the objective, the reasons behind it, the target audience(s), and the interests and ideologies embedded in the study are **transparently claimed, described, and justified.** This is crucial for future studies, at a time in which the advent of climate change as a driving issue in public and private decision-making is drawing a growing number of young professionals to join the ranks of experienced scenario producers, and in which scenario teams are being increasingly called on by a diversity of stakeholders not already acculturated to these exercises.

In this context, the present Framework modestly provides guideline to scenario producers, with the following **long-term goals**:

- Increasing the degree of **integration of science in future studies** so as to ensure greater internal consistency of the scenarios they describe. This holds true for the laws of physics which are well established for power systems, for the integration of physical limits (planetary boundaries and resource depletion) in scenarios, but also for insights from social sciences, which are typically neglected in future studies when it comes to behavioral models and to desirability issues.
- **Fostering the culture of transparency** regarding the data, the models used by future studies and the interests of those who participated in the study production, in order to foster greater trust in the scenario community.
- **Improving the integration of stakeholders in scenario production and in scenario reporting.** At the scenario production stage, sharing with various stakeholders leads to increasing the trust they have in the future study and to reduce biases from ideology and interests. At the reporting stage, descriptions of scenarios should be *concrete* enough for every interested stakeholder to understand what the scenario implies for them. This is a necessary condition for a healthy and democratic debate about these scenarios. In other words, counterparts to the proposed transitions (e.g., increase or decrease of GHG emissions, resource consumption, monetary costs, effects on employment and so on) should be explicit for all the transition stakeholders (companies, citizens, decision-makers, unions, etc., that is, virtually all the actors of society given the issue at stake).
- Fostering better **popularization of the models used and their outputs**. Most of these models are highly complex so a sufficient amount of resources should be dedicated to their popularization during study production. Popularization increases understanding and trust. It also reduces the risk of keeping unsaid ideology or interest embedded in the model.

Throughout our Framework, these objectives are concretely derived into recommendations associated with the various topics tackled by future studies.

Future studies seek to answer a set of driving questions. These questions lead to setting a time horizon for the study, a descriptive (geographical) perimeter, and a sector scope.

- Future studies within our scope are long-term studies, setting time horizons from 15 to 50 years in the future.
- They are large scale studies (at least at the country scale).
- Their sector scope is composed of two separate scopes:
    - **The *core system* is the system described as undergoing the transition.** In our studies, the core system is a **subset of the energy system**, most often the power system supply-side (the system ranging from power production plants to the sockets in dwellings, in industries and so on), or the whole power system (including the demand-side composed of all the appliances which "consume" electricity), or the whole energy system (including all the other energy carriers: oil, natural gas, coal, uranium, heat and so on).
    - The ***surrounding systems*** are the systems described as "impacted" by the transition of the core system. They typically include **environmental systems, social systems and economic systems**.
- Most of the future studies within our scope are brownfield studies (meaning that they describe a transition from the current situation) as opposed to greenfield studies (describing a snapshot situation of the core system).

Our Framework provides guidelines for ensuring transparency regarding all these framing aspects of a future study.

Study producers then select (or design) a model to help them answer their driving questions. **The model is a computational tool based on a simplification of the core system** and the systems surrounding it (the economy, society and the environment). The model is intended to provide a consistent description of the evolution of the core system to the scenario producer so this description can become part of the narrative elements that constitute the scenario.

The simplification of the real world in the model is necessary and leads to choices on what to represent from reality, and how to represent it. **These choices are not neutral and may impact the ability of the model to provide useful information to address the driving questions.** We recommend that the choice of model be thoroughly justified with regard to the driving questions. Modeling teams and scenario teams are not always the same: the scenario team often buys modeling services from a modeling team. Justifying the choice of model first requires that the scenario team sufficiently understands the model, its biases and the questions this model has been designed to address.

A future study generally **describes and compares several *scenarios***, following a study structure which depends on the message the study wants to convey. These scenarios fundamentally differ from the *levers* they activate, the *objectives* they set for society, and the *uncontrollable uncertainties* they explore. Each of the scenarios is framed by a *storyline* which ensures the consistency across the hypotheses taken as inputs in the selected model. This storyline is dynamic and describes how the input hypotheses (also called the *boundary conditions*) consistently evolve through the scenario timeframe. Our Framework investigates these framing aspects of scenarios, and provides guidance for more transparency in their definitions, their descriptions, and the reasons behind the associated choices.

Once the model has run the different scenarios, scenario producers investigate its outputs. From these outputs, they select the narrative elements they want to publish, and blend them with their hypotheses in order to tell the different stories of their scenarios. These narrative elements are about the evolution of the core system and that of the surrounding systems. **The choice of which outputs to publish reflects the vision of the scenario producer on what is important to look at from the societal viewpoint.**

Outputs related to surrounding systems are often called "impacts" even though in reality the core system and the systems surrounding it interact bilaterally. Societal stakeholders (citizens, households, associations, companies, decision-makers and so on) are primarily interested in these impacts (as opposed to changes in the core system) because they directly affect their activities and lives. Our framework proposes **that scenario producers describe all the impacts in a very concrete way**:

- Impacts on the environment (such as GHG emissions) interest a large part of civil society.
- Impacts on the economy potentially interest all the actors of society (through purchasing power, competitiveness, investment needs, sunk costs, global and local labor evolution, etc.).
- Impacts on society mostly interest households and citizens, through behavioral changes, the desirability of the transition, the quality and security of energy supply and so forth.

Our framework suggests **communicating the results through a multi-indicator dashboard rather than through integrated, opaque values.** Internalizing externalities within a single cost indicator is a risky affair as uncertainties on the values to choose for each externality are at best considerable, and at worst so large the obtained cost indicator cannot be of practical use for informing decision-making.

The results may be further explored through uncertainty analyses. Qualitative and quantitative methods can be used. The goal of such exploration is to highlight risks posed by the occurrence of uncertainties within a given scenario. Indeed, some of them may lead to completely different outcomes in the scenario, that is, completely change its overall story. **Not performing such an uncertainty analysis potentially leaves major blind spots for decision-making.** We recommend scenario producers to detail their strategies on uncertainty analyses.

We also recommend quantitative results should be published accompanied by **considerations on the number of significant figures expressed in these results and the ranges of uncertainty assigned to them**. Without such consideration, no comparison across scenarios should be performed.

Finally, we provide guidance for comparing narrative elements from different scenarios to draw conclusions addressed to the target audience, in order to improve the transparency of the links between model outputs, published narrative elements and the conclusions drawn.

B. TF#2: Energy transition models

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

A model is a simplified representation of a real system. It represents entities and interactions between different entities through logical rules or mathematical equations. Due to computing constraints, the number of entities represented and interactions is limited. The number of time steps at which they can be represented is also limited. Hence spatial and temporal resolution, as well as the level of disaggregation of the entities represented are limited.

Modeling is the craft of simplification. But modeling the energy system is an extremely complex task, as the energy system is itself highly complex. The more complex the model, the larger the amount of data required to calibrate and update it, and the greater the resources needed to maintain it.

The structure of the model is driven by the questions it seeks to answer. For example, if the question is about the effect of a given lever, then the variables and parameters corresponding to the lever in the model must be tunable. The variables corresponding to its effects must be outputs computed by the model which must also represent the mechanisms linking the lever to its effects.

In our Framework, we endorse the view that **scenario readers should be able to understand a model through the story it tells about how the energy system works,** rather than through a technical description of the algorithms underlying it, just as a book reader is interested in the story told by the book rather than in the material composing the book.

Existing model classifications poorly highlight the stories told by models. They seem to address modeling professionals rather than the users of models or scenario readers. However, the different scopes (geographical, time horizon and sector scope) belong to these classifications, and they provide information about the story told, by giving the boundaries within which it takes place.

The "Model methodology" provides insights on how the transition agent(s)[1] decide(s): **optimization methodology** represents a world driven by the search for global optimality, such as a least cost trajectory with a maximum cap on greenhouse gas (GHG) emissions; **equilibrium methodology** represents a world driven by perfect and balanced markets; **simulation methodology** represents a world driven by rules applied year after year by several deciding agents. **"Model foresight" refers to whether deciding agents are able to perfectly foresee the future, or to base their decisions on past information.**

Instead of classifying models in the existing classifications, our framework **encourages scenario producers to concretely describe the main *entities* represented in their models** (actors and objects), their resolution and aggregation levels, and the **main *interactions* between entities**. In a word, we recommend to use concrete concepts to tell the transition mechanisms at work in the model.

[1] Transition agents are the agents who drive the core system evolution in transition scenarios.

C. TF#3: Boundary conditions for energy transition scenarios

Boundary conditions are the links between a scenario storyline and the computational model used to describe the evolution of the core system. They sum up in a quantified way the narrative elements of the storyline, and are inputs for the model.

As their name suggests, boundary conditions are primarily the conditions applying to the boundaries of the core system considered. Hence, they depend on the core system selected. In reality, this core system interacts with surrounding systems which are not necessarily modeled. This is why hypotheses about these interactions must be posed so the core system can be simulated by the model as driven or constrained by these conditions.

In future studies, the boundary conditions of the energy system are typically lifestyles and behaviors, available technologies and their evolutions, demography, macroeconomic evolution, and the evolution of industrial activity including offshoring patterns, policy frameworks, prices of imported goods and materials, prices of fuels and the availability of local resources (see Figure 3).

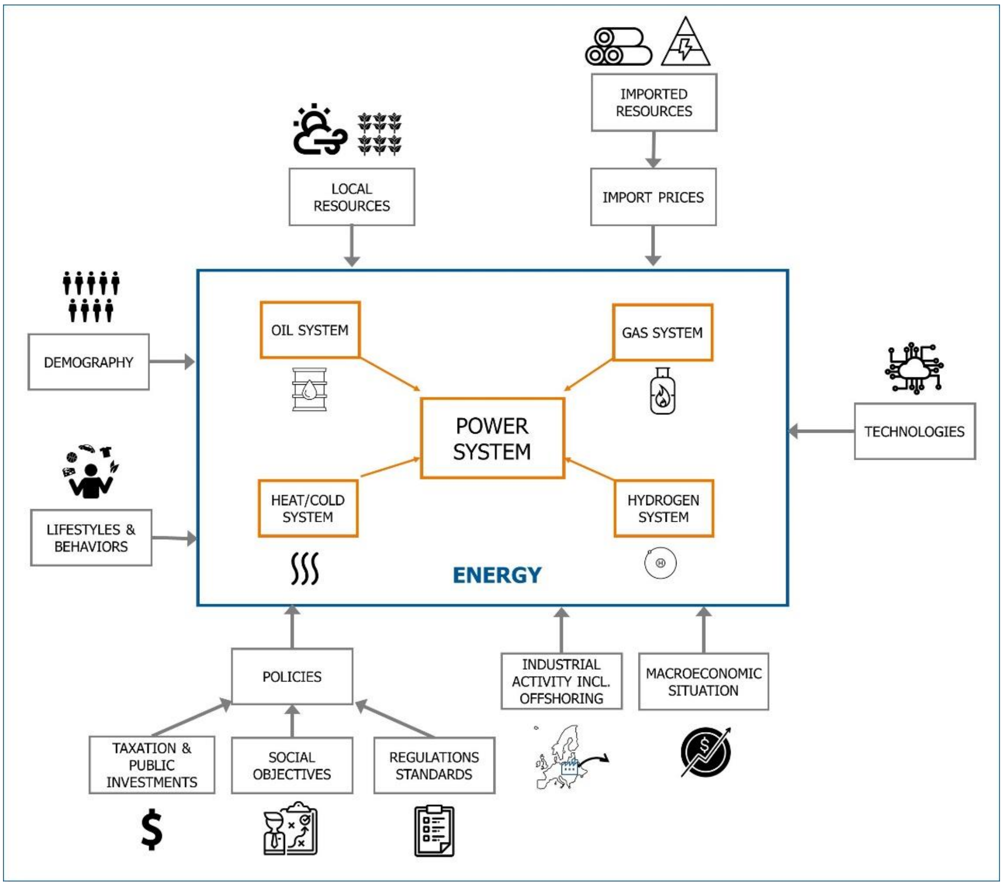

Figure 3: The usual boundary conditions for the energy system and the power system in future studies.

Boundary conditions also depend on the model selected. Indeed, some models represent more than just the core system. When a model represents parts of the surrounding systems, we say these parts are *endogenized* in the model. Endogenization requires extra modeling, that is, a simplification of the endogenized entities and mechanisms, and requires extra data. For example, the evolution of available technologies may be endogenized through learning rates.

Our framework seeks to foster **transparency on the selected boundary conditions and the endogenized parts of the surrounding systems.**

It also seeks transparency on the **integration of *physical limits* (planetary boundaries and resource depletion) in scenarios**, whether they be embedded in boundary conditions, endogenized, or not taken into account. We note that future studies generally take into account GHG emission limits, though sometimes poorly (especially for Business As Usual (BAU) scenarios, which never take into account the potential impacts of climate changes on the economy). However, other physical limits are completely ignored by most future studies.

We discuss some **critical weaknesses of future studies regarding the choices made for boundary conditions**:

- Assumptions about available technologies and their evolutions play a key role in scenarios, both in terms of core system evolution (what technology mix emerges) and in terms of impacts on surrounding systems. However, **studies are often very vague in their justification about the drivers of these technological evolutions**. Our Framework calls for a collective effort for more transparency on this point.
- Demography is always seen as independent from anything else. However, this hypothesis may well be questioned, especially for BAU scenarios in which climate change increases.
- Prices of imported goods and materials are not considered in future studies (for example, prices of technologies do not depend on the price of the materials they are produced from), which reflects the **absence of consideration on material criticality issues**.
- Gross Domestic Product (GDP) is sometimes used as a boundary condition whose role is to ensure the consistency between consumption and production (in monetary value) in the scenario. GDP hypotheses are justified with a narrow diversity of storylines produced by a narrow diversity of actors. As a result, GDP hypotheses all look alike across future studies: a steadily growing economy stabilizing at a positive growth rate. However, economic growth is uncertain, and may be a potent driver of results. **The lack of diversity in GDP hypotheses is a collective blind spot for energy transition scenarios**. Our Framework recommends discussing this issue.
- Assumptions on fuel prices suffer the same limitation as those on GDP: the diversity of narratives and hypotheses across future studies is narrow.
- The evolution of industrial activity is a boundary condition for some studies, driving the evolution of energy demand but also of surrounding systems (employment, the cost of technologies depending on where they are produced, environmental impacts depending on where the industry settles). Regardless of the importance of this hypothesis, **future studies do little to justify the evolution of industrial activity they select, even for scenarios describing an evolution which runs against the observed trends**.

Our Framework encourages scenarios producers to go beyond these limitations by providing more qualitative elements to justify these key hypotheses.

If the core system is the power system, additional boundary conditions framing the evolution of the power system must be added, such as **carrier shifts on the demand-side** (e.g., mobility going electric instead of oil-based impacts the evolution of the power system), and interactions between energy carriers, such as the development of technologies to convert one carrier into another (e.g. cheap power-to-gas technologies may impact the evolution of the power system).

Also, geographical boundary conditions must be selected, such as the **evolution of neighboring power systems** and of their corresponding interconnections.

Our Framework recommends describing the evolution of these boundary conditions transparently, and justifying them in the scenarios.

D. TF#4: Long-term evolution of energy consumption in energy transition scenarios

In this section, we explore how demand is handled in future studies, and propose a framework for efficiently discussing energy demand and the levers necessary to act on it.

Energy demand is seen and dealt with as a driver of the energy system in most future studies. Demand is considered as totally independent of the energy system in power system studies and as highly independent of it in energy system studies, in which demand evolves only slightly when the energy system evolves through price mechanisms.

In reality, energy demand and the energy system co-evolve, deeply influencing each other. The energy system exists in our daily lives through very material elements such as sockets, gas-stations, and so on; their mere presence greatly influences our consumption behaviors and lifestyles.

1. Critical limitations of future studies with regard to the evolution of energy demand

We first review the **practices employed to compute energy demand in future studies**. We observed three main approaches:

- The ***behavior-based*** **approach** starts from observed behaviors and imagines what effects on them the activated levers would have.
- The ***GDP-based*** **approach** starts from a GDP boundary condition and derives consumption by various sectors of activity.
- Power system studies use external hypotheses for power consumption directly, or they define their own aggregate hypotheses. These hypotheses are then used as boundary conditions for their models.

All these approaches generate physical inconsistencies across the energy flows described in scenarios. Typically, the energy required to perform the transition of the energy supply-side is never consistently included in the energy demand. The EROI (energy return on energy invested) concept is useful to understand the idea that the energy system consumes energy itself (self-consumption), through its construction and its operation. During an energy transition, more energy is needed to perform the transition than when no transition occurs. In addition, for some transition, the evolving energy system may be associated with an overall higher self-consumption. Such effects may have large macroeconomic impacts, such as lower amounts of energy to sustain our lifestyles. **As future studies do not properly represent energy flows and as they do not discuss this issue, they do not inform about their ability (or inability) to properly inform on lifestyle issues.**

We conclude that future studies should thoroughly substantiate this issue if lifestyles and the desirability of transitions are to be seriously discussed.

As already introduced, **energy system evolutions may influence energy consumption. Rebound effects are a typical case of such influence.** A rebound effect is the reduction in expected gains from a policy, or from market and/or technological interventions aimed at reducing energy consumption, because of behavioral or other systemic responses. Rebound effects are complex effects, some of them emerging from macroeconomic behaviors. They are described in academic works as significantly increasing energy demand, by at least 20%, compared to the expected gains of the measures implemented.

Future studies on the power system, and technical studies on the energy system, assume energy-service demand is independent from the energy system. Hence, they cannot handle rebound effects apart from qualitative considerations. We observed that they simply do not discuss rebound effects.

Future studies on the energy system that simulate price mechanisms assume weak links between the energy system and energy demand (through these price mechanisms). As a consequence, they are able to describe some aspects of rebound effects, but not all of them. Only a few explicitly discuss rebound effects.

We provide guidance to scenario producers to **tackle and discuss this potentially key issue relating to energy demand**: detecting the measures likely to generate such effects in their scenarios, describing additional measures aimed at reducing rebound effects, explaining how rebound effects are already described, and so on.

2. Efficiently describing and discussing the evolution of energy demand and the associated levers

Generally speaking, scenarios explore two types of lever when it comes to energy demand: energy sufficiency (also referred as sobriety) and energy efficiency. We show the use of these terms is more related to the subjective notion of comfort[2] than to objective concepts.

In order to collectively foster efficient discussions on energy demand and the levers driving it, we produced a framework for informing a behavior-based approach.

In this framework, we explore concepts useful to **precisely describe levers acting on energy demand, with a broad classification of levers**: *demand sobriety, technical and organizational efficiency, technology shift, load rate increase and energy efficiency*. We provide examples of such levers, show how they relate to demand evolution, and provide considerations on their co-benefits and the potential loss of comfort they induce. These concepts apply to different *energy service systems* which fulfill different human needs.

We recommend to scenario producers to define the energy services systems they want to study and then to clearly describe the levers on demand activated in their scenarios, using these concepts. This would **improve collective discussion on these levers by using a common, efficient and precise language**.

In this discussion, we show that levers other than pure energy efficiency may lead to a loss of comfort although these levers may also be associated with co-benefits. In other words, the lever of **energy efficiency is the only one which avoids difficult discussion about what is desirable and what is not**. In addition, energy efficiency does not contradict, or even points towards the sustainable development goals (if one neglects the impacts of producing the associated technologies): better access to energy services, lower levels of pollution and so on. It comes as no surprise that this lever is used extensively **and is often the only demand-side lever activated** in future studies.

This collective *de facto* choice has collective consequences:

- The scenarios described assume corporations bear all the transition efforts through technological improvement.
- The scenarios described assume no action is required from individuals or States, apart from buying and using more energy efficient technologies.
- The debate on energy transition launched by these future studies explores the question of technologies (their costs and impacts) but **neglects the geopolitical, political, institutional and cultural questions**.

As most future studies focus on technologies, we recommend that scenario producers concretely substantiate their narrative elements relating to technological evolutions.

With the help of the concepts developed in our framework, we describe the practices of future studies which use a behavior-based approach. We review those practices for each energy service system considered in future studies: in the building sector, the mobility sector, the freight sector, industry and the agricultural sector. We also suggest that future studies should **specifically consider the Information and Communication sector and the recycling sector as they may be very dynamic sectors** in a majority of transformational scenarios.

Energy demand is dependent on the climate and may be impacted by climate change. The most obvious changes affecting demand are those linked to weather sensitive demand, such as demand for space heating and cooling. But other changes can be expected, mostly changes related to deeper adaptations to the impacts of climate change.

We observe that no future study considers the concrete effects of future climate change on demand. We recommend that scenario producers should discuss their strategy regarding these effects, especially for scenarios with significant climate change.

[2] Typically, levers leading to a loss of comfort are in the sobriety category whereas those not associated with a loss of comfort are in the energy efficiency category.

E. TF#5: Lifestyles and consumption behaviors in energy transition scenarios

This section investigates the causes of changes in lifestyle and consumption behavior, as evoked in future studies and as dealt with by behavior sciences.

Energy is at the core of our lifestyles, having a strong influence on public health, economic inequality, employment, and even social stability and international relations. Energy is embedded in our socio-cultural systems, as one may realize when thinking about the changes brought about by the electrification of our lifestyles, or by the uptake of massive oil production.

Some future studies recognize the importance of the psychological, sociological and cultural determinants of energy demand which complement the usual technical and economic approaches. Integrating lifestyle and behavior considerations in energy transition scenarios makes them more robust to social reality, and provides useful tools for decision makers to understand the social risks associated with a given scenario.

Lifestyles are generally described as influenced by two components:

- **The present context**, composed of social, physical / material and economic contexts.
- **The internalization of the past context surrounding the individual**, that is, a more or less conscious memorization of past experiences[3] which still influence current practices, intertwined with an expression of one's inner tastes. Such internalizations are usually depicted as values, cultural capital, sense of identity and so on.

Lifestyles and consumption behaviors are deeply intertwined: lifestyles influence consumption, and in turn consumption (through the experiences and material environment it produces) influences lifestyles.

Some behaviors require more time to evolve than others. Typically, behaviors linked to convictions, values, identity, and social norms are deeply rooted in individuals: they have high inertia. Habits and routines also have a certain inertia, even though it may be lower than for the previous category of behaviors. Individuals play different roles in life: individual, household member, citizen, worker, decision-maker, and so on. Each of these roles is associated with different behaviors, each associated with different inertias.

Inertia emerges in part from the fact that **behaviors are maintained by the incentive structures in which individuals evolve, whether these structures be physical and material, social, or economic**. As a consequence, changes in lifestyles require a sustained change in these incentive structures.

However, within the context of energy transition, **issues of acceptability arise if behaviors subject to high inertia are required to change quickly**.

Most studies do not consider behavior change in the transitions they propose. We observed **four types of study when it comes to how behaviors are modeled**:

- No behavioral model: the scenarios of these studies (implicitly) assume behaviors do not evolve at all, hence they do not describe behaviors.
- Opaque behavioral model: these studies propose some behavior changes but do not explore why they change and neglect the issue of desirability.
- Market-based behavioral model: these studies assume no lifestyle changes occur except those induced by market mechanisms. During the scenario timeframe, individuals are described as pure consumers behaving as has been observed in the past. In these studies, the only levers acting on consumption are market levers: carbon pricing, and better information for consumers. When carbon pricing is implemented, desirability issues are "hidden" in the carbon value. These studies do not discuss desirability issues.
- Cause and effect behavioral model: these studies describe and discuss behaviors and lifestyles. Some of them explain qualitatively the reasons why behaviors would change in their scenarios. These studies are a minority.

[3] Such as received education, upbringing, past interactions with significant others, book reading, and any significant past experience.

We observe that **desirability issues are neglected by most studies, because they neither discuss behavior changes nor the levers required to foster them**.

In addition, collectively speaking, the absence of discussion on behavior changes may lead scenario readers, including decision-makers, to believe that no measure can be taken to promote lower energy consumption through lifestyle changes, or that such measures are not needed.

In reality, behavioral sciences (and in particular behavior analysis) have clearly shown that behaviors can and do change during the course of a lifetime, and have explored the determinants of these changes. Behaviors can evolve "naturally", through grass roots, cultural changes, or they can evolve because of policy changes, economic changes, and changes in their material or physical environment.

"Grass roots" changes are already under way in some countries. Detecting them is key to integrating them in scenarios, whether it be to describe how they grow or how they disappear. **Forgetting these trends may lead to neglecting desirability issues** in scenarios which assume they disappear.

The shortcomings we observed about the way future studies handle behavior changes have two main consequences:

- **Ignoring interesting political and economic levers** (such as public investment in infrastructure, bans, imposed standards and so on) by focusing only on market-based levers.
- On the contrary, **underestimating behavioral inertia and hence overestimating the speed of behavioral changes**. This bias is equivalent to neglecting certain non-desirability issues induced by the speed of change. Such a bias may appear in studies using a cause and effect model, when strong assumptions on behavior changes are made, or in studies using the market-based model when strong changes are assumed in consumption behaviors. E.g., some scenarios assume mass building insulation without dealing with the subject of desirability of the investment decision and of the works involved.

These shortcomings could be limited by integrating social and behavioral scientists in scenario teams instead of relying only on engineers and economists. We warmly recommend scenario producers to integrate social, and in particular behavioral, sciences in their studies.

In order to **help scenario producers to link behaviors to policies**, we developed a **three-stage framework** for discussing this link from the standpoint of behavior analysis.

- In the first stage, we show that behaviors are driven by several *driver categories*: close relationships, society, and the physical environment. By modifying the incentives posed by these categories, behaviors are more likely to change.
- In the second stage, we discuss four *policy levers* which act on one or several levels of influence, in turn increasing the chances of behavior changes: communication and information tools, public space design tools, economic tools (taxes and subsidies) and legal tools (obligation or ban, standards).
- In the third stage, we explore the different *lever activation modes*, that is, the ways policy packages can be framed, and their effects on the efficiency and the desirability of the policy levers to alter behaviors. For example, policy packages should implement non-contradictory incentives. Incentives should stay in place long enough. And so on.

We argue that this framework will help scenario producers to **describe how and why behaviors change in their scenarios**. It will help them propose relevant policy levers to foster behavior changes in their scenarios. It may also lead more scenario producers to seriously explore the question of behaviors and to investigate the effects of behavior changes in energy transitions, by providing the appropriate tools.

F. TF#6: Long-term evolution of the power system supply-side in energy transition scenarios

After having extensively discussed the question of energy consumption, its links to lifestyles and consumption behaviors, and the links between policy levers and behaviors, we turn to energy supply.

On the supply-side, our framework focuses on the power system.

1. The power system and its architecture

The power system (supply-side) is a complex technical system which is highly intertwined in our daily lives. This technical system follows well established laws of physics. In particular, instant balance between produced energy flows and energy consumption must be kept at all times.

Energy flows are transmitted in the form of an alternative current, characterized by a given beat with a fixed frequency. They travel through a power network, the grid.

Electricity production is ensured by a set of technologies. Two main classes of technologies can be distinguished regarding the transition of power systems:

- Those directly **producing alternative current**, which can directly inject energy into the grid: thermal power plants that convert heat into power (using coal, natural gas or biogas, oil, uranium, concentrated solar power (CSP), geothermic heat, etc.), hydropower, tidal power, etc. The current they produce is alternative because it is generated by rotating magnets on an alternator. Alternators are often very massive and have great inertia. These production plants are called Synchronous Machines, as their rotations are all synchronized to the unique beat of the grid. **Their high inertia ensures the beat cannot be modified too quickly in case a problem occurs somewhere in the power system.**
- Those **producing direct current**, which **must be equipped with a converter** in order to inject alternative current into the grid. Most of the "new" renewable plants, called Variable Renewable Energy Sources (VRES) belong to this category: wind turbines, photovoltaic panels (PV), wave energy technologies, marine current technologies, etc. **These technologies do not participate in beat stability through inertia.**

Given the way a power system operates, the larger it is, the cheaper and the more secure it becomes. There are three main reasons for this:

- Economies of scale for production units can be obtained when a large group of consumers is gathered, as production units can be larger.
- Linking production capacities[4] enables better reaction to contingencies (unexpected events) on production or consumption with the same total capacity, because the inertias of Synchronous Machines sum up.
- Linking production (or consumption) units through the grid leads to an aggregated production (and consumption) whose fluctuations are smoother than individual fluctuations.

The architecture of the power system can be highly centralized to highly decentralized. Traditional power systems are centralized: the power flows from large power plants to individual consumers. A decentralized power system is composed of more or less autonomous smaller-scale power systems, with power flows being exchanged bi-directionally along the grid, between these smaller power systems.

The **architecture of the power system evolves depending on what actors drive its evolution**. Supposedly, if large actors such as the State or large corporations drive it, the power system will remain largely centralized. If smaller actors such as local territories, or small businesses, drive it, it will tentatively evolve towards a decentralized system.

Within our scope, no future study explicitly presents scenarios with a highly decentralized power system. We recommend to scenario producers to explicitly discuss the architecture of the power system in their scenarios.

[4] The capacity refers to the power which is delivered by plants, and by extension to the plants themselves.

In this section, we review the practices of future studies on the long-term transition of the power system. Then, we propose a transparency framework for future studies to describe the characteristics and their evolutions of the power system supply-side technologies involved in their scenarios.

2. The power system is driven by a small number of different rules in scenarios

In future studies, the **power system evolves over the long-term following different rules**. These rules may be said to be applied by actors who drive the evolution of the power system through decision-making.

We observed **two approaches on how time is taken into account** in the decision-making of these actors:

- **A time-based approach**, in which decisions are taken at each time step (e.g. each year) about how the power system will evolve. These decisions are based on information from the previous time steps.
- **An intertemporal approach**, in which decisions are made about the power system based on perfect knowledge of all the events occurring during the scenario timeframe. In other words, a single decision is made about the whole pathway taken by the power system over the scenario timeframe.

We observed that **three different categories of rule were applied** by the actors driving the power system evolution:

- The *cost-optimization rule* drives the power mix by adding up costs involved along a transition pathway, usually in the form of a total system cost and applying a minimization function to it in order to find the least-cost pathway. This rule is always applied with an intertemporal approach: the least-cost overall trajectory is selected.
  This rule is applied using data about the cost (and its evolution) to produce energy for each production technology. However, more constraints apply in order to get a more realistic power system (otherwise only the least expensive technology would develop): typically, tests are performed to check the proper hour by hour power supply.
  When summing up costs, the "cost of capital" (that is, how much financers earn for financing) is generally included through so-called WACC (Weighted Average Cost of Capital) values, representing the expectation of financers in terms of revenues.
  The results of future studies using this rule are likely to be sensitive to cost hypotheses. Hence, we recommend that these future studies explore the uncertainty on their cost hypotheses.
- The *portfolio rule* builds up the power mix using "rules of thumb" to decide which technologies to add in the existing mix. The goal of these rules is to get a secure system favoring a variety of technologies without necessarily obtaining the most cost-optimal mix of technologies. This rule is applied with the time-based approach.
  Typically, grid evolution due to growing demand and due to the selected technologies is considered as a by-product of the mix: grid costs are not considered in the selection process for building the mix.
  The portfolio rule is based on "traditional" good practices for designing a centralized power system supply-side, which have proved efficient to ensure supply security.
- The *preference rule* builds up the power mix based on a selected storyline which sets overall preferences for driving the power mix.

For all these rules, **decisions taken on the evolution of the power system are highly sensitive to the availability of technologies, and to the characteristics of the available technologies. These characteristics and the reasons for their evolutions should be highly transparent.**

3. Describing the power system technologies and their evolutions transparently

We propose a **framework for describing the technical and economic characteristics of power system components transparently.** We first note that these characteristics may evolve during the scenario timeframe, either through boundary conditions or through endogenized learning rates (which set a law on how technologies evolve as a function of their implementation, in order to represent improvements due to experience).

Then we recommend to scenario producers to **substantiate various aspects of technological evolutions in their scenarios, for production plants, for storage technologies and for the grid.** To this end, we propose to present these aspects in transparency tables. Substantiation is very flexible and can be adapted to the specific scenario and data sets used. For example, if characteristics are not used in a scenario, the substantiation may start as: "this characteristic is not used in scenario X because…"

The goal of this substantiation is two-fold: **greater transparency** towards the scenario community, that is, all the stakeholders interested in the production of future studies; **improved comparability** of the hypotheses of different scenarios by gathering them in standardized tables. Both objectives participate in fostering trust among the scenario community and improving the overall debate on energy transition.

The first table (see Figure 4) gathers the technological characteristics of production plants. A dozen characteristics are described and guidelines are provided to substantiate them and their evolutions in the table. For example, technology maturity, life duration, dispatchability, resource predictability, load factor, availability factor and considerations on impacts from climate change should be substantiated.

	TRL	Unit capacity	Energy yield	Life duration	Dispatchability level	Dispatchability main constraints	Resource predictability	Resource potential
Wind								
PV								
Nuclear								
Gas								
…								

Maximum installation rate	Production profile	Load factor	Availability factor	System storage function	Ancillary services	Impact from climate change

Figure 4: Table of technical characteristics of production units.

The second table (see Figure 5) gathers the technological characteristics for storage technologies. Maturity, type of application, storage capacity, power output, reaction time and so on should be substantiated.

	TRL	Type of application	Storage duration	Storage capacity	Power output	Cycling capacity	Efficiency	Storage potential	Operational constraints	Impact from climate change
Pumped hydro storage										
Compressed air energy storage										
…										

Figure 5: Table of the technical characteristics of storage units.

The third table (see Figure 6) gathers the economic characteristics of technologies. We recommend that commercial maturity, CAPEX, OPEX, investor-LCOE/LCOS, WACC, and considerations on employment linked to the technology should be discussed in future studies.

	CRI	CAPEX	OPEX	i-LCOE / i-LCOS	WACC	Employment data
Hydro						
Gas						
Batteries						
…						

Figure 6: Table of economic characteristics.

The fourth table (see Figure 7) gathers the environmental characteristics of technologies.

All production plants and storage technologies interact with their surrounding environments in two ways: by extracting resources from them and/or by releasing substances into them. By and large, this participates in several issues that can be either local or global. Some of these interactions can be easily measured and expressed as physical quantities, while others are of a more diffuse nature and are better expressed qualitatively.

The environmental impacts described in Figure 7 should be substantiated for all technologies. If they are relevant for the scenario, they should be discussed qualitatively, and if possible quantified.

	Material criticality	Land use	Water use and pollution	Climate change	Air pollution	Solid waste	Biosphere
Hydro							
Gas							
Batteries							
...							

Figure 7: Table of environmental characteristics.

We also propose several social characteristics of technologies, such as landscape impact, safety risks, and other human ecology impacts (noise, smells, etc.) in a last Table.

Grids are most often simplified into "copperplate" models, that is, national power systems are represented as a single copperplate into which all production plants and consuming devices are plugged. Such a model cannot be used to inform on the impacts of power system changes in the power grid. A few models go beyond this simple representation so as to explore impacts on the high-voltage network (transmission network). However, no model explicitly represents the lower voltage network (distribution network). Hence **no future study precisely describes the effects of the transitions it proposes on the distribution grid and on its proper operation.**

This may be a serious limitation for scenarios proposing high shares of renewables, as VRES are mostly plugged into the distribution grid. We recommend that scenario producers should substantiate their strategy on this question.

Smart grid equipment is usually presented as Information and Communication Technologies (ICTs) enabling the low-cost integration of VRES without decreasing the reliability of the power system. However, when it comes to concrete descriptions, only a few main functions are deemed mature enough: storage, demand-side management, VRES curtailment, automated fault detection and dynamic estimates of flow capacity in power lines. Most of these functions are already discussed in our framework. Here we discuss demand-side management.

For dwellings, some services requiring power can be easily shifted in time: water heating thanks to the thermal inertia of hot water tanks, space heating thanks to the thermal inertia of dwellings, charging electric vehicles due to the storage function in the car and the fact that cars are not always in use. However, depending on the situation of each household and the proposed managed demand-side uses, certain desirability issues may emerge. For industries, each case is specific and some industrial plants may accept to shift their demands at a lower price than others.

We recommend scenario producers to **concretely discuss the smart grid techniques involved in their scenarios and their desirability**.

G. TF#7: Power system operation in energy transition scenarios

In this section we provide information on the different aspects of power system reliability to highlight which of them must be considered, and in which type of scenarios they must be considered, in order to **properly integrate the physics of power systems in future studies**. A fundamental characteristic of these aspects is the wide range of time scales they cover (from milliseconds to decades), implying great difficulties in modeling them in future studies. Similarly, these aspects cover a wide range of geographical scales (from the local scale of a power grid segment to the national scale of the whole power system).

However, these constraints must be taken into account to propose scenarios in line with the laws of physics. For scenarios **with larger shares of variable renewables, some of the physical constraints of these power systems with variable renewables turn out to be more complex** than they are for traditional, highly-centralized, stock-energy-based[5] power systems.

Power system reliability refers to the probability of the system's satisfactory operation over the long run. The reliability criterion is crucial: models used by power system planners show that the reliability requirement significantly constrains possible power systems. In addition, the higher this requirement, the higher the total system cost.

Several adverse events can occur in a power system: mismanaged consumption or production variations, weather events, technical failures, and human mistakes. Such events may alter three key stability parameters of the power system: frequency stability, voltage stability, and rotor angle stability. We first tackle these aspects before dealing with so-called ancillary services.

1. Frequency stability

Frequency represents the instantaneous balance between electricity supply and demand. A frequency decrease corresponds to a lack of injected power compared to demand; a frequency increase corresponds to a surplus of injected power compared to demand. Such situations should not last for too long or the power system may stop operating properly.

Flexibility is the ability of the power system to cope with frequency variations. In other words, it is the ability to control the power supply-demand balance. **Flexibility must be considered at different forecast horizons**, because the available flexibility levers have different reaction times: a few levers are extremely fast, and a growing number of levers can react over longer times. The other reason is that the need for flexibility depends on the occurrence of unexpected events whose probabilities grow when the forecast horizon is further in the future.

The need for instant flexibility is called **inertia**, because traditional power systems show a physical tendency to stabilize frequency thanks to the high inertia Synchronous Machines they include, and to the load, that is, to the various rotating devices (industrial electric motors, washing machines, etc.) that are plugged in and operating.

The need for fast flexibility is called **reserves**. Reserves are an automatic or manual action at the production or load level that serve to restore frequency stability and frequency value in a timely fashion, in case an imbalance occurs.

Other types of longer-horizon needs for flexibility exist (infra-day, daily, weekly and seasonal flexibility).

The different levers used to tackle short-horizon flexibility needs (inertia and reserves) are the following: conventional power plants supply most of the inertia; in addition, they can act quickly and modify the power they deliver to provide reserves; load management and demand response can act fast and provide reserves but this may lead to desirability issues, as already discussed; storage devices can also act fast but are not yet economically competitive versus VRES curtailment and gas turbines (even with a carbon price); VRES can provide some flexibility if their inverter is properly tuned and if they produce when needed.

To tackle longer-term horizons, these levers are accompanied by market mechanisms to ensure enough power producers will be ready to produce at a given time.

[5] That is, whose production plants are based on energy stocks such as coal, water in altitude, uranium, gas, etc. as opposed to energy flows such as wind, run-off-the-river water, sun radiations and so on.

VRES integration leads to greater infra-daily to seasonal flexibility needs, due to the variability of VRES. It also leads to a **greater need for reserves**, due to the uncertainty on their production, which is greater than that of traditional power plants. Finally, it leads to **greater needs of inertia**, because they are connected to the grid through power electronics inverters which cannot provide instant inertia (these items of equipment have a non-zero reaction time).

Regarding inertia, specific equipment such as synchronous compensators can **provide inertia to the power system at low-cost**.

Very fast (and fast) reserves can be provided by batteries, by properly connected wind turbines when they produce, or by curtailing VRES production in case of overproduction. However, the effect of these very fast reserves is limited in time, which is a limitation as lower speed reserves may take 10 minutes to take over.

Finally, at all forecast horizons, increasing the geographical perimeter of the power system in addition to ensuring the effective centralized control of flexibility levers leads to a reduction in flexibility needs through the effect of aggregation.

Most future studies explore seasonal to infra-daily flexibilities in their scenarios, through "hour-by-hour" simulations of the power system at different steps of its evolution.

Only **a few studies explore reserves**, by simulating the uncertainty of VRES production.

Regarding inertia, **it is not simulated yet in any study**. Qualitative analyses are proposed in the latest studies on power systems, though without taking into account the inertia of the load.

A few studies explore the case of power systems with a high share of RES (including hydropower, biogas plants, etc.), and in which production is ensured 100% by VRES at certain times of the year. This is a very specific situation as the role of "beat-leader", usually played by Synchronous Machines, is not present to sustain the beat. Such cases are still under research.

We recommend scenario producers to **transparently describe their strategies relating to all these flexibility forecast-horizons**. They should list those they consider, their methods of assessing demand/supply balance, and provide substantiation for those they do not consider.

2. Voltage stability

Voltage evolves through time following supply and demand variations as well as grid topology variations. At a given time, voltage evolves through space as a function of the topology of the connected equipment and plants.

Voltage should be maintained around its nominal values at all points of the system. Equipment connected to the grid as well as power plants require the voltage to be maintained around its nominal value. Indeed, these items of equipment are designed to operate for contractual voltages. Equipment can be worn or damaged if it is too high. If it is too low, the current intensity can become too high for the lines. Low voltage can induce transformer and power plant malfunctions as well as make the operation of the grid more difficult.

Voltage control is ensured by a set of equipment and by the synchronous machines. These levers for voltage control can be activated at different speeds, as with frequency stability. Voltage control can also be provided by inverter-connected VRES if they are producing, but at lower levels than synchronous machines for an equivalent capacity.

However, these issues can typically be mitigated at moderate cost by installing additional equipment in charge of the control. Hence **the impacts of inverter-connected VRES generators on voltage control can be assigned low priority when planning long-term transition**.

3. Rotor angle stability

Rotor angle stability is the state in which the power system is when all the alternators of plants run at the same electrical speed (this common speed is the frequency of the power system). Under specific, anomalous situations, generators can start running at different speeds. Power system frequency falls out of sync and the power system becomes unstable.

Such a situation is typically filtered in traditional power systems by the frequency control systems of synchronous machines. With high shares of inverter-based VRES, this instability would not be filtered out because the production plants would simply follow the different frequencies instead of synchronizing them. A technology called "grid-forming" inverters can be used to avoid this behavior, albeit at additional costs which are still unknown (though potentially high).

We recommend scenario producers to **discuss this question and describe the strategy they propose to deal with rotor angle stability**.

4. Other ancillary services

The **protection system** supports the power system and acts as its sensory and actuation organ for detecting faults and correcting them. It must operate correctly for the power system to react fast enough to fix or isolate faults.

In traditional, centralized power systems, the protection system has been designed for this architecture. Hence faults are detected through sensors which may no longer detect them if larger shares of inverter-based VRES are installed, or if too much capacity is connected to the distribution grid (VRES are mostly installed at the distribution grid level).

Different technologies can be adopted to overcome these problems. We recommend scenario producers to discuss this issue and assess the impacts (e.g., cost) of the different technologies developed in their scenarios.

Black start is the ability to restart the electricity system in the case of a total blackout. Most thermal power stations consume electricity when starting up (e.g. powering pumps, fans and other auxiliary equipment), so special provisions are needed when black-starting the system, by making sure generators are present that can start without an electricity supply.

Typically, system operators use hydroelectric plants (which can generate as soon as the sluice gate is opened), diesel generators or battery systems, which can then start a gas turbine, which can then start other power plants (for example).

With high shares of VRES, conventional solutions can still be used (hydropower, diesel generators).

However, for very high shares of VRES, the "beat leaders" may be too weak to provide the beat on which generators can synchronize. This question is still under research.

We recommend scenario producers to discuss this question and provide their strategies with regard to it.

H. TF#8: Impact assessment in energy transition scenarios

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

In this section we cover the general aspects of impact assessment: transparency about which impacts are assessed in the study, and the possible consequences and risks of not taking into account the other impacts; transparency about the activities considered as generating impacts in the evaluation, consistency between this choice of activities and the driving questions and transparency about the methodology used to compute/describe the impacts.

This section is an introduction to the more specific sections about the desirability of transition, and the economic assessment, employment assessment and environmental assessment linked to it. In these sections, the various aspects dealt with here are applied to the corresponding surrounding systems and detailed accordingly.

We show in this section that **considering different interactions with surrounding systems may lead to significantly different study results**. This is the case when an interaction limits the possible scenarios through feedback loops from surrounding systems. Hence, we recommend to scenario producers to **explicitly declare the choice of the interactions they explore**, and justify why they do not include other interactions.

We then explore the different aspects of **defining the perimeter of activities which will be included as "impacting"**. First, we discuss the territory *vs* footprint approaches: in the territory approach, only the activities taking place within the geographical perimeter are considered, whereas in the footprint approach the activities that have been necessary to ensure the consumption within the geographical perimeter are considered. In both approaches, transport occurring both inside and outside the geographical perimeter can be dealt with in different ways. We recommend scenario producers to describe the approach they selected.

Then we propose that activities considered in the assessment be listed in a clear *inventory*.

A clear "system perspective" can be defined if the study seeks to provide information in the interest of society as whole, as opposed to specific actors'. This perspective includes all the activities which are required to provide energy services to the end-consumers.

Choosing a precisely defined system perspective avoids:

- Comparing indicators which do not cover the same points of view;
- Using indicators to influence society-wide decision-making whereas they do not cover a global service: e.g., using indicators on specific technologies to influence decisions on the whole power system.

Then, we recommend that the inventory should be in line with the driving questions, and that the conclusions of the study should be in line with the inventory. Otherwise, the conclusions drawn may be misleading.

For each interaction considered, we finally recommend making the assessment methodology transparent, and we discuss so-called "horizon effects" which can bias the assessment results.

I. TF#9: Transition desirability in energy transition scenarios

The desirability of the transition refers to whether a proposed transition is desirable for the different actors composing a society. In the case a transition does not seem desirable by some actors, they can raise questions of acceptance and generate conflicts with the transition planner(s). Desirability usually appears to the world in its "negative" form, through visible conflicts or resistance, hence it is sometimes called an "acceptability issue". Acceptability and desirability are really two sides of the same coin: how people envision changes.

As previously mentioned, social aspects are largely neglected in scenarios whereas proposed transitions may encounter considerable hurdles in the real world because of people's possible reluctance towards these transitions or the way they are led. As suggested in this section, the concept of desirability may be useful to integrate these aspects in the design of future studies: **by better understanding why conflicts emerge in the real world, scenario producers can better take desirability and acceptability considerations into account** in their scenarios.

In this section, we develop a framework to efficiently deal with desirability issues in future studies. This framework is based on three types of conflicts transitions may generate:

- *Uncertainty conflicts* emerge when opponents are worried about the potential impacts of the projects on themselves, their local environment, their jobs and their lifestyles (as inhabitants of a territory and workers in a given sector). For example:
    - Uncertainty on how **energy security** will evolve, in particular **energy prices**, for example through time-of-use pricing, may generate this type of conflict. We indeed show that in developed countries, energy is now perceived as a basic need because of its perceived role in ensuring survival, good health, a decent life, and the ability to engage in expected patterns of life. A lack of energy is sometimes called **"energy precarity."** We provide guidance to scenario producers to discuss and, if needed, efficiently take into account this issue of desirability.
    - Fast transitions require fast changes in the structure of the workforce. Workers may have to face **unemployment** and follow **training** courses to acquire new skills. Some may have to **move to different regions** depending on where the efforts to achieve the transition are concentrated. Some **fields of expertise may become useless**, and the cultural and social status associated with them may disappear. These situations may lead to desirability issues. We recommend that scenario producers discuss this risk.
    - Finally, the installation of new infrastructures may lead to conflict with local inhabitants. Such conflicts may be generated by **impacts of these infrastructure on human ecology** (industrial risks, noise, ice shedding, smells, and so on), or on landscape (presumably place attachment and the meaning that the new infrastructure may have for the inhabitants play a role in conflicts due to impacts on landscapes).
- *Essential conflicts* emerge when opponents contest the nature of the proposed project in general (as citizens), such as a global policy for energy transition planning. For example:
    - **Inconsistencies between policies and societal incentives, or across policies**. Any energy transition policy may have impacts on social inequalities or may affect sectors of the population differently (owners of polluting cars, residents of energy inefficient buildings, etc.). These impacts may lead to acceptance issues raised by the losers in the proposed transition. In other words, a **global consistent vision** should include considerations on equity within society as well as considerations on how to accompany those who stand to lose the most or those who cannot fulfil their basic needs. Also, **policies should be in line with other incentives in society** (for example, if cars are still heavily advertised and seen as a positive social marker, a ban on cars in some areas may generate conflict).
    - **Sunk costs**. This term means the share of capital invested in an existing asset that has not been recovered when the asset stops operating. Thus, sunk costs appear whenever an asset is closed before the end of its economic lifetime. The asset is said to be "stranded." For society, sunk costs reveal an inconsistency between past choices and new objectives. Coal power plants or polluting cars may generate sunk costs in case laws banning them are passed. Sunk costs are a typical transition risk, and **raise the question of burden sharing: their allocation to different sectors of the population may generate conflict**.

    - Global impacts on the environment. Depending on each culture, citizens may not accept that global impacts on the environment occur. For example, the **environmental cause is growing** in Western Europe. If their countries continue deteriorating the environment, these citizens may generate conflicts. Considering such a risk is particularly important in BAU scenarios which usually assume minimal change in human activities.

  For each of these substantial risks of conflict, we recommend scenario producers to discuss them, and if needed to detect in their scenarios if such risks exist and to justify why no conflict occurs.

- *Structural conflict* emerges when the project proposed originates from an illegitimate actor, that is, an actor who is not considered to represent the general interest. We show that structural conflicts are a growing risk for some regions of the world and we detail mechanisms fueling these conflicts based on the French example. **Whatever the nature and content of the projects proposed that constitute the transition, as long as they are carried out by actors whose legitimacy regarding their support of the general interest is in doubt, it can be expected that such projects will give rise to an increasing number of structural conflicts**.

  Personal data management by corporations or the State may be a specific motive for structural conflicts.

  We recommend scenario producers to discuss these aspects of structural conflicts, and if needed, to justify why these conflicts do not occur in their scenarios.

In addition, two ways to avoid these conflicts (consultation procedures and storytelling) are developed in our framework:

- **Consultation procedures** may be organized in scenarios; scenario producers should provide narrative elements about the results of these procedures, and take into account the consequences of these results (e.g., additional costs to adapt the projects).
- **Storytelling and narratives** are known to change ideas and behaviors in readers or listeners. Future studies present different scenarios, which are such narratives. However, only future studies from civil society appear to address the greater public and integrate more storytelling elements and/or more references in values (solidarity, equity, autonomy, etc.) in the quest to fire imaginations. Such storytelling may foster the desirability of the transitions described. Scenarios can be envisaged that convey such stories aimed at influencing civil society and fostering the desirability of a given vision.

We recommend scenario producers to discuss the idea of desirability emergence, and we provide guidance if they resort to it.

Finally, we provide general guidelines to better take into account desirability issues in future studies.

J. TF#10: Environmental assessment of energy transition scenarios

The environment is an organized, dynamic and evolving system composed of natural elements (physical, chemical and biological) and of human elements (economic, political, social and cultural) in which living organisms operate (including human activities) and in turn affect the same living organisms (and human activities) either directly or indirectly, immediately or on the longer term.

In other words, the environment is complex and dynamic: organisms affect the environment by acting within it; these environmental changes may in turn affect the organisms directly or indirectly, following complex feedback loops with different temporalities.

For human societies, feedback from the environment may be delayed (such as the carcinogenic effects of air pollution, or extreme weather events due to GHG emissions), may occur remotely (such as the impacts of climate change which may happen anywhere regardless of where the gaseous emissions took place); they can be combined (such as climate change effects and habitat fragmentation effects on biodiversity, in turn affecting crop productivity); they can be non-linear with threshold effects (such as climate change with regards to the amount of GHG emissions, or unexpected effects on trophic chains due to human activities).

In this section, we tackle the following interactions between the evolution of the energy system and the environment: **greenhouse gases (GHG) emissions; impacts on the biosphere; material criticality; land use; air pollution; water use; solid wastes (hazardous and nuclear); and noise**.

The studies we reviewed generally include considerations on GHG emissions; a few consider air pollution; a few consider mineral resource use (a component of material criticality). Other impacts are rarely talked about, and never quantified.

For each interaction we describe its nature, the activities generating it, its possible impacts for human beings, and how these issues are considered in future studies.

In particular we focus on **material criticality**. This complex issue is rarely addressed in future studies even though it might be a game changer for the feasibility of some scenarios. The corresponding field of research is new, but developing quickly.

Material criticality refers to the dependence of a region on mineral resources. The study of the constraints on the supply of a material resource is complex because these constraints are multidimensional: geopolitical, economic, linked to production, environmental, and social.

We recall that transition scenarios each require different metals in different amounts, and provide information about a few key metals. Then, we review all the criteria which can be part of a criticality analysis: geological availability, geological dependence between materials, dynamics of production development, recycling process, substitution possibilities, demand growth, concentration of production, political risk, social constraints, environmental constraints, and concurrent uses.

Finally, we discuss recycling. We claim it is a key lever for transitions, but has inherent limitations. We review these limitations and present mechanisms which can foster the development of recycling industries in scenarios.

We recommend to scenario producers to define and justify their strategies relating to all these interactions. If needed, guidance regarding the precise definition of the interaction studied, the definition of the inventory of impacting activities, and the modeling methodology is provided.

K. TF#11: Economic evaluation of energy transition scenarios

This section addresses scenario economic evaluations.

Questions on economic evaluation are often subject to high expectations since it remains an important aspect of fact-based political discussions. However, studies present their own insights and results using very disparate methods, with different scopes and indicators. As a result, it is very difficult to use a set of studies to establish new conclusions collectively, to make knowledge emerge, and thus better inform the debate on energy transition.

We address this issue by proposing a methodological framework, which would allow scenario producers to employ a **flexible and clear method for the economic evaluation of their studies, and to participate in a common effort by sharing a standard for greater transparency**.

This methodological framework is based on a system perspective and is structured around three elements: the possible **perspectives for cost evaluation, a power system inventory, and the choice of adapted cost indicators**. It is designed to carry out economic evaluations of a *technical* nature (as opposed to evaluations of a *macroeconomic* nature). The system perspective has been described in other studies (Agora Energiewende, 2015) and the framework structure has been inspired by previous work from RTE (RTE, 2017). We present a combination and exploration of a resulting structure that we believe can constitute a clear and usable tool for scenario producers to foster and enlighten discussions. This framework has been used to describe the practices of several studies and its application seems relatively simple.

Our framework has been detailed for power systems, but the same approach could be generalized for the energy system as a whole thanks to some specific adjustments (such as adding all the conversion systems enabling the conversion of energy carriers into another form). The philosophy would remain the same.

The system perspective consists in assessing costs required to *make the system work*, and only those costs. Total system costs consists of a reflection of the real overall effort, of the amount of time spent and resources mobilized to build and operate the system assessed. Therefore, the system perspective contrasts with both focuses on technologies and on the perspective of specific actors.

Here is an overview of the content of this technical file.

The first part introduces the distinction between the costs of a technical and macroeconomic nature, as well as general considerations on the use of cost indicators. Then, three categories of future studies are defined as a function of the levers they activate: those activating supply-side levers only, those activating supply-side levers and energy efficiency (on the demand-side) and those activating supply and demand-side levers, including demand sobriety. The type of economic evaluation, the inventory and the choice of cost indicators indeed depend on the category of the study.

The core elements of the methodological framework are then described as followed:

- ***Possible perspectives* are the angles from which the assessed costs are being examined**. It can be either system as a whole or one specific actor such as the State, electricity system actors, or the final electricity consumers. We explore this categorization: not being clear about the perspective chosen in an analysis leads to classic misunderstandings and only the costs assessed from the same perspective can be compared. It should thus be clearly stated before any comparison. We also highlight the fact that the often mentioned "costs to society" are not associated with any specific perimeter in future studies and thus that a "system perspective" with a clear inventory should be preferred. In addition, the **system perspective better enlightens public decision** (even though the perspective of specific actors can also be useful to provide complementary insights).
- *Power system inventory* gives an **overview of all the power system components (demand-side and supply-side) requiring expenditures to build and operate the system** during the scenario timeframe. It details all the subsystems related to electricity production, network (transmission, distribution and interconnection), consumption (including energy demand management), storage, power services, operationalization, carrier shifts, electricity consumption and adaptation and repairs due to climate change. The inventory should contain the elements which differ among scenarios so as to ensure the efficient comparison of costs between scenarios.
- **Choices of adapted cost indicators** for informing either the system perspective or the perspective of specific actors are then explored. To compare and evaluate costs from a system perspective, a table of *system technical cost indicators* is presented and three specific system technical indicators and their respective uses are defined and explored:
    - *expenses shape,* to visualize how the financial effort of one scenario evolves over time,
    - *comparative costs,* to properly compare two scenarios,
    - *absolute costs*, to understand the evolution of costs in comparison with today's situation.

  The five cost items required to calculate system technical cost indicators are presented in detail: the often-used CAPEX and OPEX, but also the electricity trade balance, future costs and past costs. Methods to calculate each cost item are described in an annex with complementary guidance and information.
- Cost elements that have to be added to **assess costs from specific actors' perspectives** (i.e., economic transfers) are discussed as well. To assess costs from a "final consumers" perspective, we provide a discussion on price and the cost of energy for final consumers.

L. TF#12: Employment assessment of energy transition scenarios

Employment assessment is part of the economic assessment, and may be said to be the labor counterpart of costs. Hence this aspect is also crucial for policy-makers. This is why it is regularly selected as an output of scenarios. **Employment is typically (if not always) assessed to show that the transitions proposed increase employment** compared to a BAU.

In our framework, we consider employment as a *need* for transitions rather than an *impact* of transitions. This definition enables asking useful questions about global job management (that is, considerations on required skills, qualification levels, mobility and training for job creations, and considerations on the proper management of job destructions).

We first discuss **global job management**, including considerations on job stability, qualification levels, the geographical distribution of jobs and the relocatable *vs* non-relocatable nature of jobs. Depending on the speed of the transition, emerging sectors requiring labor may come up against hiring bottlenecks and disappearing sectors may encounter acceptance issues from their workers.

We provide recommendations for scenario producers to discuss these issues in detail and to be transparent about their associated strategies.

In the second part, we detail the different methodologies used by future studies to **quantitatively assess the evolution of employment**.

We argue that a net assessment (that is, including both job creations and job destructions) should be performed to properly inform the societal debate. Focusing on only a few sectors of the economy usefully informs the associated actors, as opposed to society as a whole.

We then discuss the **different methods used to explore job needs in the economy in more or less depth.** So called *direct* and *indirect* effects on employment focus on the sectors which are directly involved in the energy system transition (the technical assessments focus on these effects). So-called *induced* effects are macroeconomic effects and refer to the jobs created or destroyed by the change in expenses of all the economic agents due to the proposed transition.

Other macroeconomic effects may be represented, such as money creation effects and so on. These other macroeconomic effects are typically assessed by full macroeconomic models, which potentially provide more comprehensive information on the evolution of employment than "manual" methods. However, these models rely on complex and still debatable macroeconomic theories, so that building a narrative on their results and discussing these results with stakeholders is much more difficult than with manual methods.

Each of these methods and each of these effects are explored in detail. For future studies which quantitatively assess employment evolution, guidance is provided so that they can be properly and transparently discussed in future studies.

IV. Conclusions

Scenario-based future studies are vital tools for informing public debate about energy transition, as they are tools designed to engage discussion with stakeholders on complex and uncertain subjects.

However, they are currently facing various difficulties with regards to the high expectations placed on them. In a context of growing concern about climate change, biodiversity integrity, material and energy resource criticality, an increasing number of societal stakeholders question future studies regarding several aspects, and expect more and more from them.

We believe future studies are vital tools for the debate on energy transition, and we call for significantly more resources to be poured into future studies activities.

In order to adequately inform the debate on energy transition, future studies should be more diverse, and their collective production processes should be upgraded. In addition, dialogue across future studies must be facilitated.

To this end, we produced a Framework that discusses the collective practices of future studies and provides recommendations to scenario producers on all the key topics of energy transition. This Framework is composed of 12 technical files covering over 120 key topics of transition.

In our review of the collective practices of future studies with respect to these key topics, we observed several critical limitations.

A. Future studies currently face critical limitations

1. The laws of physics are not properly integrated in some aspects of energy transition

Physical limits (planetary boundaries and resource depletion) are not discussed, with the exception of climate change. Very few studies discuss material depletion and changes in land use. Biosphere integrity is never discussed.

Climate change is taken into account through GHG emissions. However, **future effects of climate change are not discussed**, even in BAU scenarios which generally describe futures leading to high levels of emissions.

Energy flows are not properly accounted between economic production and energy demand. In scenarios, energy demand is not physically linked to the energy consumed by the energy system itself. This may be a critical limitation in the case where energy system self-consumption is significant in total consumption. Typically, during energy system transition, the energy system has to be modified, which requires more energy (e.g. for the production of new infrastructure). Secondly, the energy system obtained may be more self-consuming than the current energy system.

Finally, certain specific but **critical aspects of the power system's operation are not systematically discussed**. In particular, frequency stability[6] may not be ensured in some scenarios, because the level of reserves and inertia are not discussed. Reserves and inertia are required for the power system to remain stable and operate properly. Their lack may lead to power outages. Only a few studies assess the amount of reserves, and a few studies discuss inertia qualitatively.

[6] Frequency represents the instantaneous balance between electricity supply and demand. A frequency decrease corresponds to a lack of injected power compared to demand; a frequency increase corresponds to a surplus of injected power compared to demand. Such situations should not last for too long or the power system may stop operating normally, leading to power outages.

2. Some critical interactions with surrounding systems are not discussed

We call an interaction "critical" when its integration in the scenario could result in significant changes in the story told. **Such critical interactions are not systematically discussed**. For instance, key environmental impacts (material or energy criticality, water use, land use, etc.), upstream conditions for employment to enable the transition (skills, training structures, geographical mobility of workers, etc.), and desirability issues, are rarely discussed, even though integrating them in the narratives could radically change the story. They are typically constraining or limiting interactions which could change the story.

3. Transparency is poor in some critical aspects of the transition

The reasons for the technological improvements involved in the transitions described, from a technical or cost point of view, are rarely discussed in concrete terms. For example, no explanation is provided about what type of new design could be implemented, the amount of research needed to develop them, or the concrete reasons for their cost decrease (offshoring in low-cost labor countries, improvements in design or production processes, etc.). This aspect is particularly critical for scenarios relying on technological advances and their smooth adoption through markets.

The reasons for the evolution of industrial activities are not systematically discussed, even in scenarios involving a trend reversal compared to today. In other words, no discussion is provided about why industrial activity would increase, or decrease (offshoring patterns, relocation patterns). This may be critical for scenarios in which industry represents a significant share of energy demand.

The stories told by models are not concretely described, due to the lack of popularization of models. Models are highly complex and take a long-time to understand (or might not even be fully understandable by a single person in some cases). It typically takes a significant effort to popularize results, but this effort must be made to foster democratic debate on energy transition, in which interested stakeholders understand the story as applied to their particular situation.

The transition of the power system distribution grid is never precisely described in future studies. Indeed, this fine and dense network has not yet been modeled in future studies. This may be a serious limitation for scenarios involving large shares of renewables connected to the distribution grid, as they might imply significant modification of this grid.

4. The exploration of behavior changes and of desirability issues is poor, collectively speaking

Behaviors change over a lifetime, depending on the social context, the material environment, and societal environment (economy, institutions, etc.). Political levers can foster such changes.

Collectively speaking, future studies hardly investigate aspects pertaining to behavior changes and instead focus on the smooth spread of technological changes (energy efficiency) in society through market mechanisms. This should not be seen as a problem for one particular future study to investigate technological progress. The problem for society emerges when a large majority of future studies focus on this aspect while leaving other aspects unexplored. Hence, geopolitical, political, institutional, cultural aspects are barely explored in future studies.

Similarly, **questions of the desirability of the transitions proposed are hardly explored**, except as an impact on total costs (undesired projects would cost more to implement because they would have to be modified, or moved away). We show that this question is much more complex and deserves discussion in future studies.

In a word, human aspects of future studies are typically neglected. This may be due to the fact that questions about the energy system are traditionally tackled by engineers and economists. However, in the context energy system transition, its systemic and all-encompassing aspect requires studying the evolution of human behaviors interacting with it. Hence **skills and knowledge from the behavioral sciences must be included in future studies production.**

5. Economic boundary conditions lack diversity, collectively speaking

Some studies take macroeconomic parameters as boundary conditions for the evolution of the energy system. Typically, GDP drives the overall levels of energy-service demand in scenarios, which in turn to a great extent drives the evolution of the energy system (both its supply and demand sides). In other words, in these scenarios, the GDP hypothesis determines society's capacity to modify and use the energy system. Thus, the GDP hypothesis is crucial.

However, **GDP evolution hypotheses are typically very homogenous** across these future studies: stable and growing steadily, stabilizing at a low but positive growth rate on the long-term. These hypotheses emerge from a few narratives produced by a few actors, whereas many other consistent narratives could be imagined. Again, this should not be seen as a problem for a single future study, but may become one for society as no future study explores alternative GDP pathways.

The situation is the same for hypotheses about fuel prices. Unlike GDP, fuel prices do not drive the size of the overall energy system in scenarios. Rather, they drive the internal choices within the energy system, across different technological choices.

6. Common discussion frameworks are missing to take the energy transition debate to the next level

In future studies, the vocabulary used to describe the evolution of energy demand is usually poor, composed of two concepts (energy sufficiency and energy efficiency). Similarly, the vocabulary used to think the evolution of behaviors fostered by policies is nonexistent. The vocabulary used to think desirability issues is typically composed of one concept (NIMBY). The vocabulary to discuss cost indicators and their meanings is missing.

Standardized ways of discussing hypotheses and results are missing, making it difficult for the scenario community to easily understand what is investigated in each future study and what is not.

In other words, the activity of future study production on energy transition could turn into a 'grown-up' science through the adoption of new collective concepts and frameworks to discuss and describe energy transition efficiently.

B. Helping scenario producers overcome these limitations and turn future studies activities into a 'grown-up' science: our recommendations

In order to overcome these critical limitations, **we propose a Framework,** which is primarily composed of the **12 Technical Files** of which this document is the Synthesis Report. The Framework, is **based on a few guiding principles**.

1. Transparency on each key aspect of the transition

In order to foster transparency on more than a hundred key aspects of the transition, our Framework, through most of its recommendations, asks for **different levels of transparency**. For each key aspect, the philosophy is the following:

- The first, basic level is that of discussing the future study's strategy regarding this aspect. The first step is to declare if this aspect is dealt with in the study. If it is not, a reason may be provided with regard to the driving questions of the study, and a qualitative impact analysis of not considering this aspect may be provided, typically to show that this aspect is not critical for the results.
- The second level of transparency is useful for the studies which indeed integrate the aspect. This level is about discussing the details of the aspect (the method used to handle the aspect, the different sub-aspects which need to be thought out and so on).

The ultimate objective of this guiding principle is that scenario producers do not neglect key aspects in their studies.

2. Constant dialogue with stakeholders

Interacting with interested stakeholders has many benefits:

- It drives the discussions towards concrete concepts, that is, concepts which are intelligible to the interested stakeholders. Stakeholder are usually closer to the real world in their domains than scenario producers are. Discussion with them fosters concrete descriptions and transparency.
- It greatly reduces the risks of embedding unsaid interests or ideologies in the future study by including inputs from various interests and ideologies.

Interactions with stakeholders can be implemented **during scenario production** to help the future study integrate these positive aspects. It can also be implemented **during the writing of** the final report. For each key topic, **descriptions must be concrete enough to be intelligible** to interested stakeholders, even if they have not participated in the study production. For example, the description of daily passenger mobility must be intelligible to any individual taking a car, a bus, a bike, etc. in their daily life.

3. Collectively achieving more diversity in key hypotheses and explored scenarios…

As presented, some key hypotheses are very homogenous across future studies. We call for a **collectively more diverse exploration of the future**. In order to foster the emergence of "out-of-the-box" scenarios describing unconventional pathways (which is one of the powers of future studies activities) to collectively inform the map of possible transitions, we recommend for these hypotheses to **discuss the "mainstreamness"** of the hypothesis selected.

Exploring failed transitions is never done either, whereas it could provide key information on the possible failures and dead ends for our societies, and how to avoid them. No explicit recommendation is provided regarding this, whereas **presenting failed transitions** should be seen as a real advance for society.

4. …while using a common vocabulary and transparency frameworks

More diversity is required in the scenarios explored, but **more homogeneity is required in the vocabulary and the frameworks used** to discuss energy transitions.

Our Framework proposes such frameworks and an associated vocabulary to collectively think and discuss several aspects of the transition: a new vocabulary to describe future studies efficiently is proposed; a framework and vocabulary to describe the evolution of energy demand and the associated levers are proposed; a framework for building and precisely presenting system cost analysis is proposed; a transparency framework to describe the technological evolutions of power system supply-side technologies and the associated key indicators is provided. We recommend scenario producers to employ them, use them and make them evolve.

C. The next steps

This Framework is a first proposal by *The Shift Project*, inspired by various experts and various published future studies. **This Framework is open to further co-construction** with those who will use it and with scenario readers.

This Framework is incomplete by nature, as it does not cover the supply-sides of all energy carriers. A next step could be to add the supply-sides of other energy carriers. For example, technical files on gas, biogas and so on could be produced, and the existing technical files updated to take into account the specificities of the gas carrier.

This Framework seeks to provide recommendations based on the practices observed in future studies. However, we did not systematically observe the practices of *all* the future studies on *all* the key aspects of the transition. Instead, for each key aspect, we reviewed a few studies to obtain a sense of the current practices and their rationales. We did not perform a review for certain key aspects (e.g. driving questions, data openness, the description of models used, etc.). Furthermore, we interpreted these practices based on the study reports and available annexes, but we did not validate our interpretations with scenario producers.

This is why we aim at producing **complete benchmarks of a few existing studies and validating these benchmarks with the producers of these studies: this will be the next step of this project.** More concretely, we want to describe the current practices of these studies in relation to the key aspects of our Framework.

To this end, we are building a **future study checklist** which gathers the recommendations proposed in the Framework. For a given future study, this checklist can be filled so as to describe how the future study answers to the various recommendations. The ultimate goals of such a checklist are that scenario producers use it as a to-do-list during scenario production, and that they fill it before publication to efficiently inform the scenario community on where their future study stands among other future studies.

From this checklist, a **"future study ID"** could be extracted, in order to synthetically inform about the practices of a given future study.

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About *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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