# Boundary conditions for energy transition scenarios

## Technical file #3

## Information and recommendations for scenario producers

This document is part of a set of 12 technical files. These files have been produced by *The Shift Project* after nearly 2 years of research and experts consultations on the different aspects of energy transition and the future studies around these aspects.

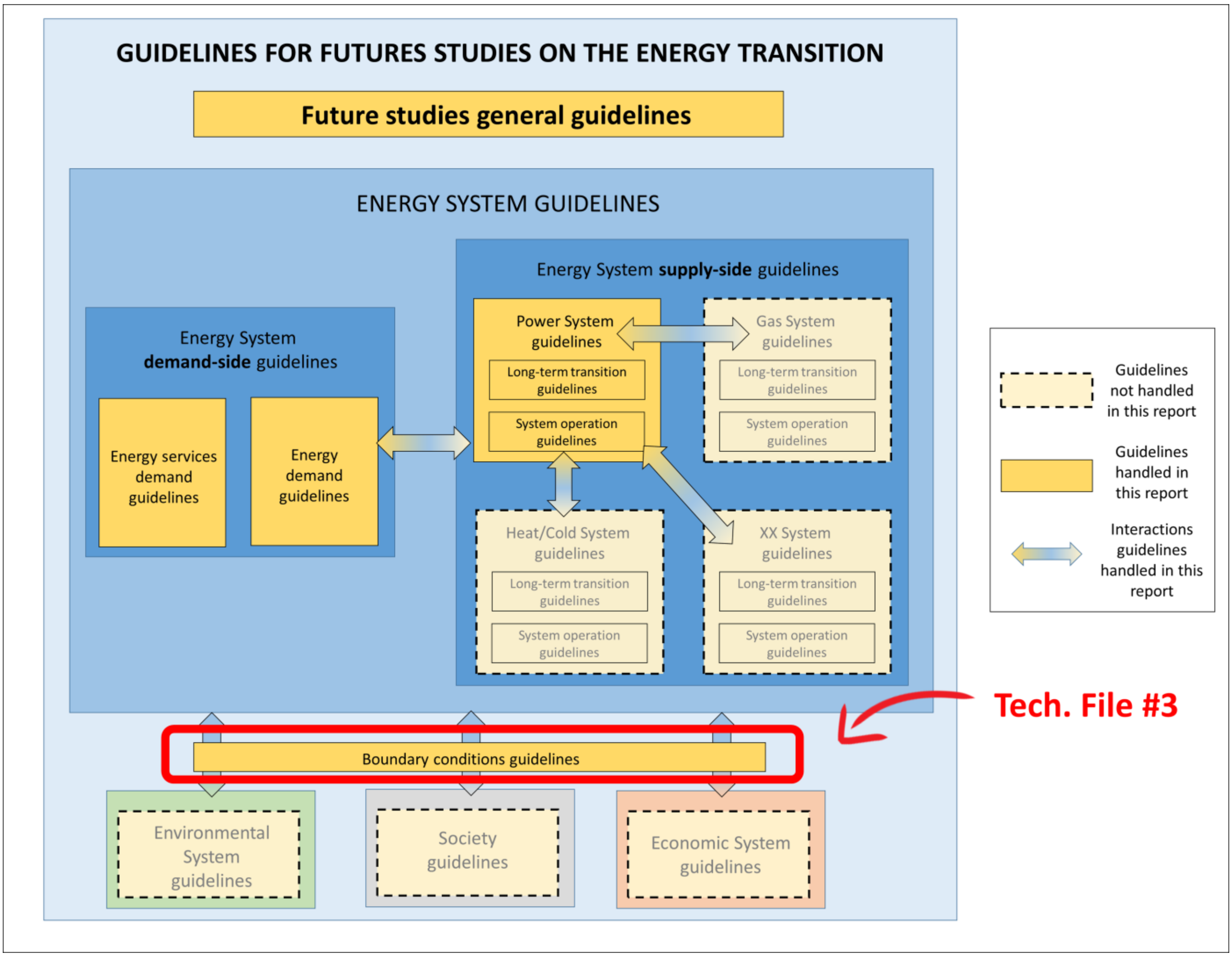
Our project, "Power Systems 2050 – Guidelines for future studies on energy and power transitions," started in January 2018, involved approximately 60 experts through interviews and workshops, reviewed more than 300 works, including about 20 future studies. The objectives and approach of this project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

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

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

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

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



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## Reading keys

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

**Recommendations to scenario producers:**

These boxes contain the recommendations for scenario producers.

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

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

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

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

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

Boundary conditions are the link between a scenario storyline and the computational model which is used to describe the evolution of the energy system. They sum up in a quantified way the narrative elements of the storyline. The notion of boundary condition is linked to what the core system actors[1] which are represented in scenarios cannot, or are not willing to, modify (Samadi et al., 2017). For example:

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

Boundary conditions are usually part of the storyline before being derived as exogenous hypotheses for the model. The storyline ensures the consistency between all the boundary conditions through narrative elements.

More technically, **boundary conditions are the conditions which are imposed on the considered core system** (the entire energy system (ES), the power system (PS), the power system supply-side…) and which partly drive its behavior. In other words, systems outside the perimeter (such as other energy sub-systems if the studied system is power system, or systems surrounding the energy system) interact with the modelled system through boundary conditions.

Boundary conditions also depend on the model which is used to describe the evolution of the ES and its surrounding systems.

The notion of boundary condition is developed in this section, after presenting notions about the energy system.

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

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

The **supply-side system** ranges from the production or import point down to the point before end-consumption of the carrier[2]; it includes self-production (e.g. from roof solar panels) and storage systems (e.g. pumped hydro storage, or batteries).

The **demand-side system** is composed of the set of equipment, appliances or industrial processes consuming the carrier[3]. For example, washing machines, cars, trucks, industrial processes, heating systems and so on are included in the demand-side system.

[1] Such as energy consumers or energy producers.

[2] From a technical point of view, the supply system goes from primary energy to the technical systems transforming final energy into useful energy, as described in (Droste-Franke et al., 2015).

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

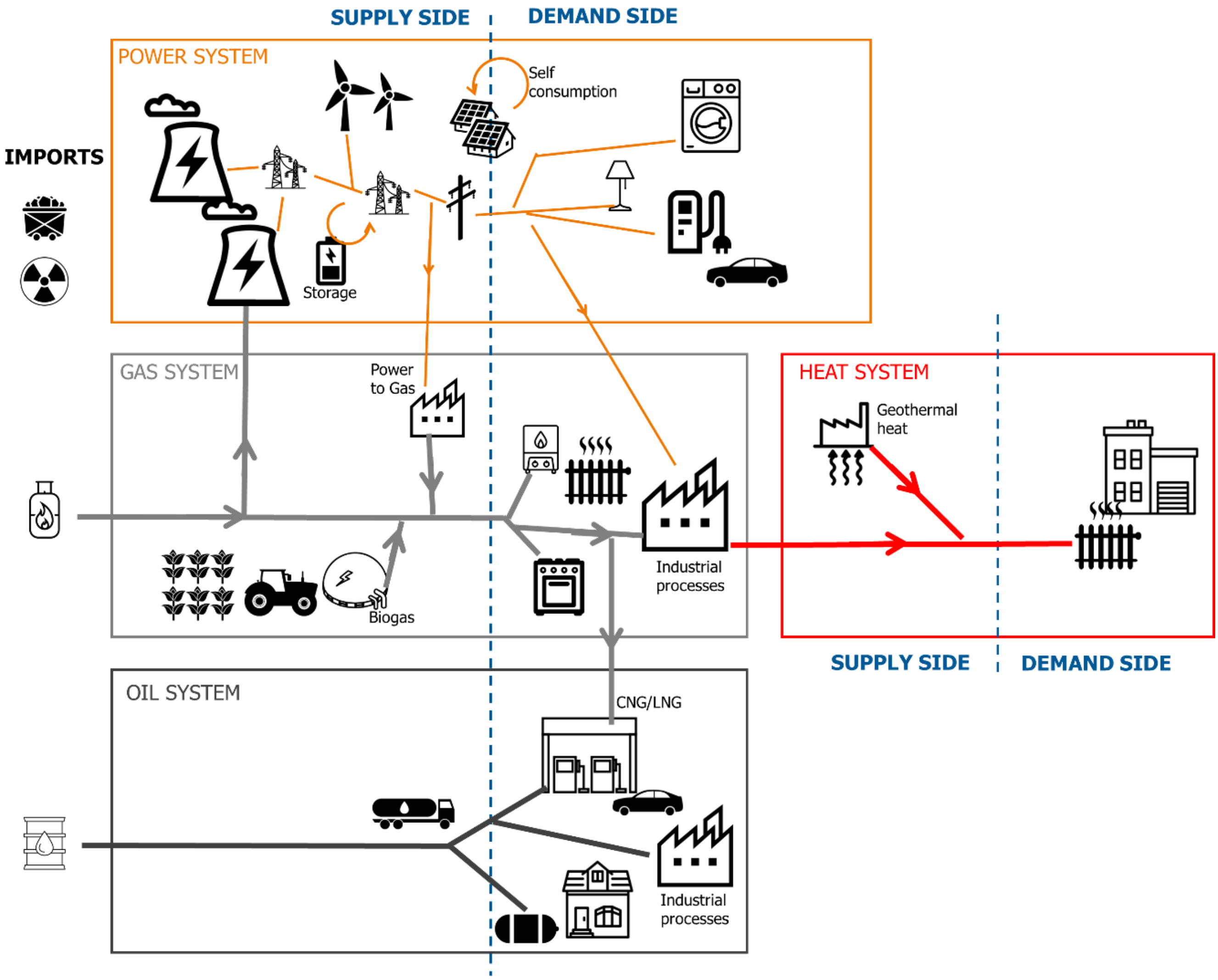


*Figure 1: Simplified description of the energy system to illustrate what we call energy subsystems (the power system, the oil system and so on) and the distinction between supply-side and demand-side for each energy subsystem. Not all the energy subsystems are represented (hydrogen, coal, nuclear and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

## B. Boundary conditions are driven by the choice of sector scope and choice of model

### 1. The choice of core system drives the nature of boundary conditions

Conceptually speaking boundary conditions are what agents represented in the scenarios cannot, or are not willing to modify. Simulated agents are actors driving the evolution of the core system and are simulated in the selected model[4]. Hence the nature of the boundary conditions is tightly linked to the choice of core system and of model representing this system.

Boundary conditions are translated in models into what we called "exogenous variables and parameters" (see future studies). Within a scenario, each exogenous variable and parameter is set to a given trajectory which is imposed to the simulated agents and entities by the modeler. However, across scenarios within a future study, those variable parameters can take different trajectories so as to show the effects of setting them differently. A boundary condition is a hypothesis that the model requires in order to run properly.

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

As studies do not cover the same core systems and do not use the same models (even for studying the same core system), the nature of these variables differs across studies.

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

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

In more details, the most usual boundary conditions for future studies on the ES are the following (see Figure 2):

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

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

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

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

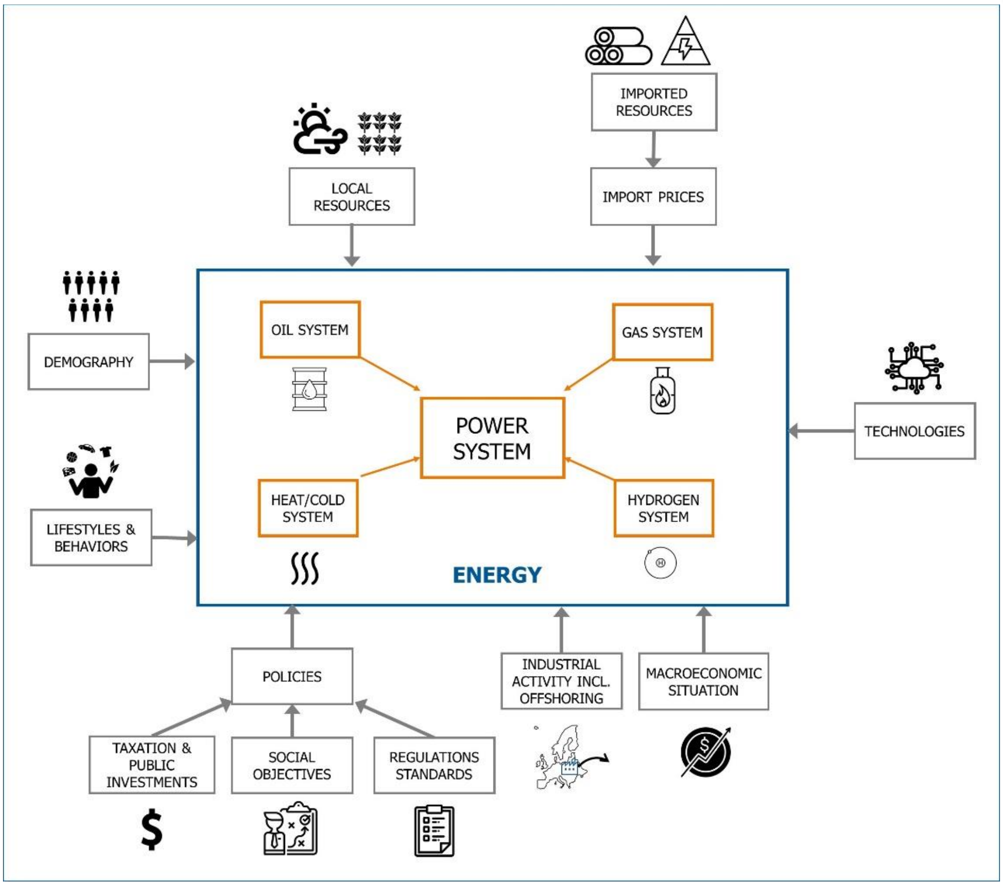


*Figure 2: The usual boundary conditions for the energy system and the power system in future studies.*

## 2. Endogeneization of parts of surrounding systems also impacts the nature of boundary conditions

Some studies use models which integrate some parts of surrounding systems, such as some aspects of lifestyles and behaviors, aspects of other parts of the economy (such as how technologies will develop), or aspects of the environment (such as how climate change can impact the economy). Here are a few examples to illustrate how this integration alters the nature of required boundary conditions.

Lifestyles and behaviors evolutions are not a boundary condition for simulated agents' models because they model behaviors by assuming they are ultimately determined by the political frame and objectives. In other words, they have *endogenized* lifestyles and behaviors by modeling them, generally through elasticities to price, or through utility functions (see Figure 3), such as in studies using PRIMES model (E3Modelling, 2018), POLES model (Keramidas, Kitous, Schmitz, European Commission, & Joint Research Centre, 2017), or the World Energy Model (International Energy Agency, 2018).

Hence these studies require hypotheses about the political frame and political objectives, about the available technologies, the evolution of their technical characteristics and prices, the prices of fuels, and macroeconomic situation, such as GDP evolution (which actually translates largely unspoken hypotheses about global constraints on the economic system).

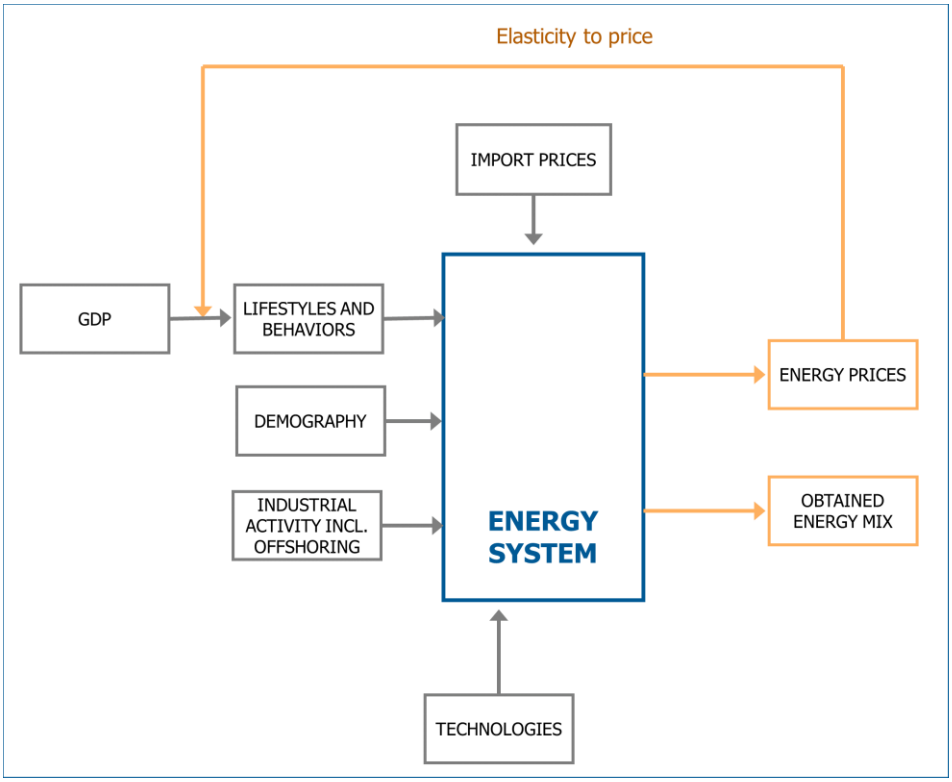


*Figure 3: Illustration of the endogenization of lifestyles and behaviors.*

Similarly, some models require as input the characteristics of each technology year after year whereas some others endogenize a part of the evolution by assuming a learning effect (see Figure 4), such as (ECF, 2010). In a way, this is equivalent to model a part of the economy, namely, the behavior of industries designing, producing and distributing these technologies. In this case, the boundary condition is one of learning effect parametrization (the technical and cost improvements with every doubling of the production, for instance).

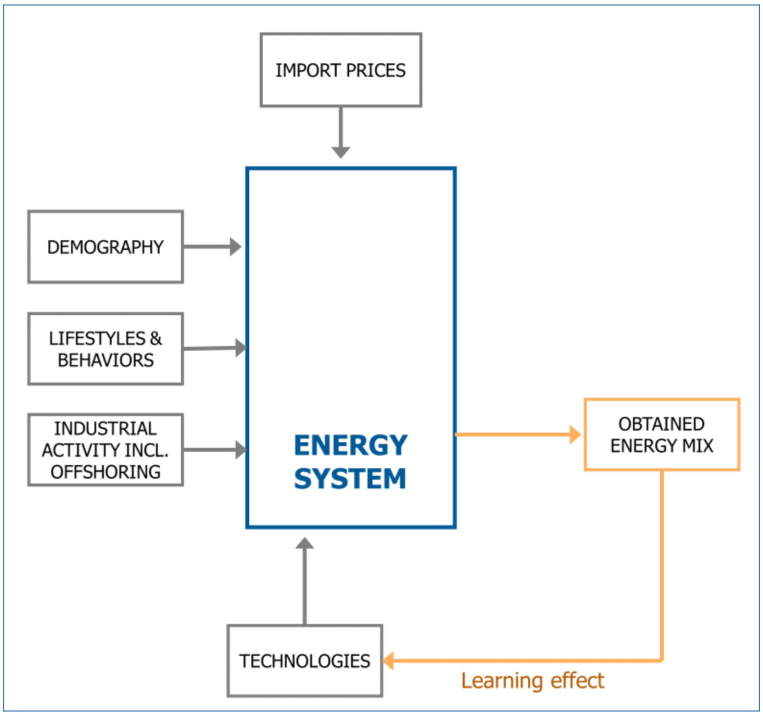


*Figure 4: Illustration of the endogenization of the learning effect of technologies.*

A few models endogenize the effects of some planetary boundaries (see below): (Bovari, Giraud, & Mc Isaac, 2018) modeled the climate change feedback on the economy through different damage functions (see Figure 5) ; (Donella H. Meadows, Randers, & Meadows, 2004) modeled the feedback loops between different planetary boundaries and the economy. Such an endogenization is equivalent to modeling (in a very simplified way) the atmosphere and its impact on the economy.

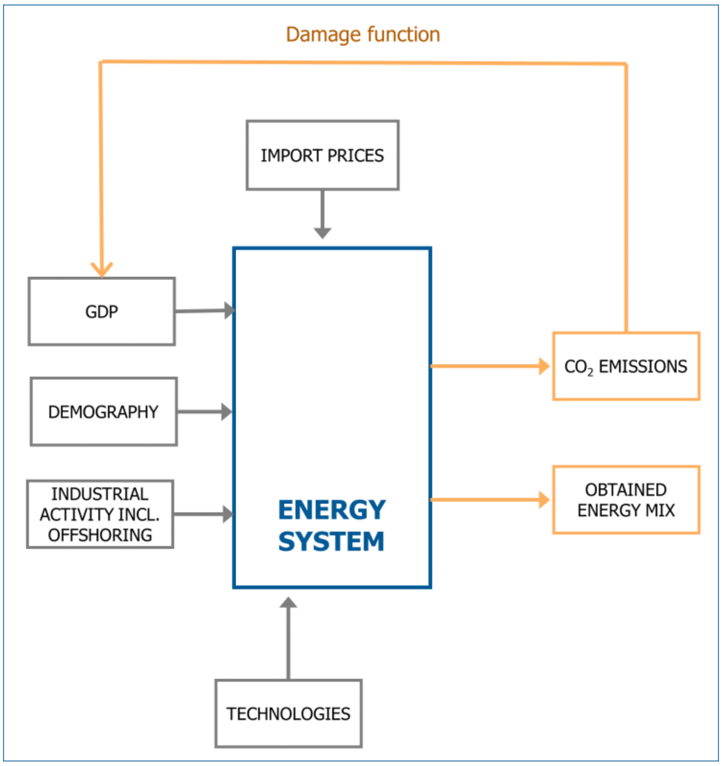


*Figure 5: Illustration of the endogenization of the effect of climate change on the economy, through a damage function.*

Thus endogenization is the integration within the model of some parts of surrounding systems, which in turn have to be modeled. This process replaces the boundary conditions which formerly set the interaction with the corresponding part of the surrounding system.

**Recommendations to scenario producers**

A list of the nature of the boundary conditions fixed for the different scenarios should be provided and justified with regards to the study strategy, choice of sector scope and endogeneization aspects. Diagrams representing the core system and its interactions with surrounding systems may be used, these interactions being either set by boundary conditions or endogeneized.

# II. In current studies, planetary boundaries and physical limits are poorly, or not at all, taken into account

In current future studies, planetary boundaries[5] and non-renewable resource availability (which we call together the *physical limits*) are not taken into account through boundary conditions.

This might not be a problem for scenarios in which the proposed energy transition prevents from coming too close to these physical limits. Often, transformational scenarios have a social objective, or policies leading to a dramatic decrease of greenhouse gases (GHG) emissions over the scenario timeframe. Hence, in these scenarios climate change may not have significant physical impacts on the economy since mitigation effort has been great enough (that is, the climate change boundary is not transgressed in these scenarios[6]). Presumably, in scenarios which do not transgress the climate change boundary, a GHG emissions assessment only is enough to show the absence of transgression.

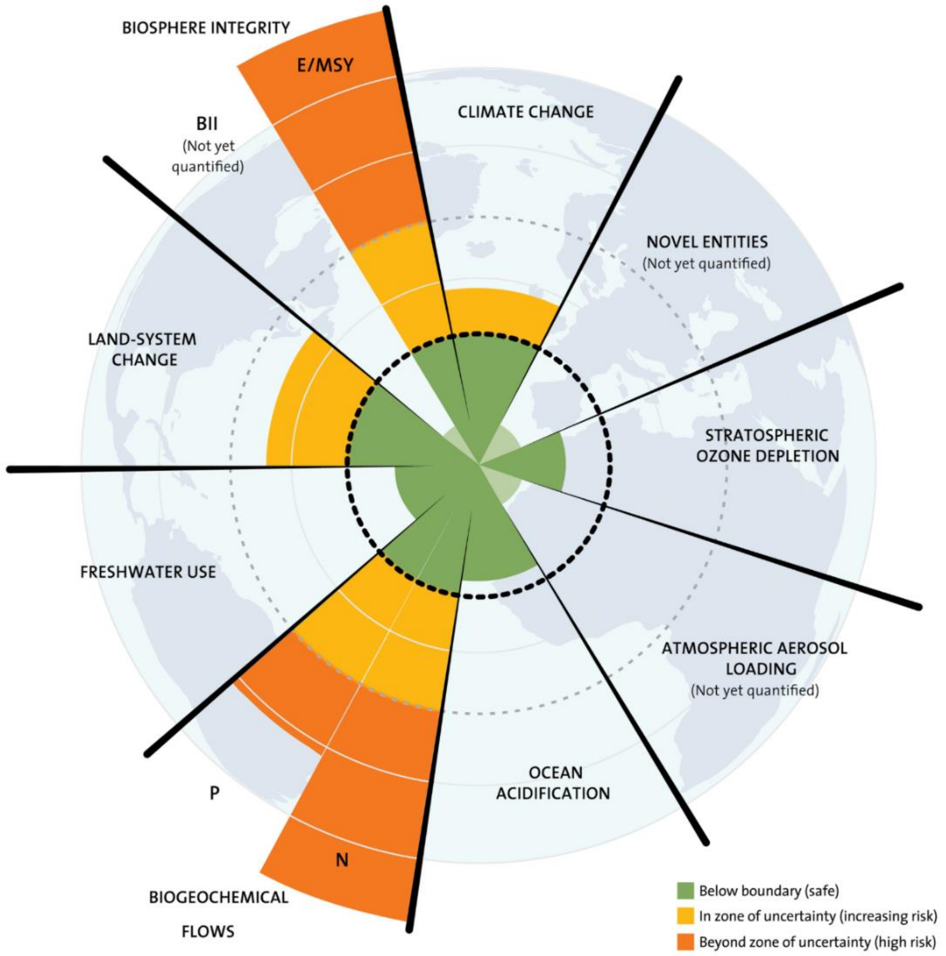


*Figure 6: The 9 planetary boundaries and how we stand with regards to the safe operating space (source: Stockholm Resilience Center)*

[5] "The boundaries define a safe operating space for humanity that should not be transgressed if we want to maintain stable conditions at the Earth System level." They are climate change, biosphere integrity, land-system change, freshwater use, biogeochemical flows, ocean acidification, atmospheric aerosol loading, stratospheric ozone depletion and novel entities. "Four of the nine Planetary Boundaries have now been transgressed as a result of human activity. These are: climate change, loss of biosphere integrity, land-system change, and altered biogeochemical flows (phosphorous and nitrogen)" (The University of Cambridge Institute for Sustainability Leadership / Kering, 2017).

[6] Following the planetary boundary framework vocabulary.

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

Hence, most studies (and even their transformational scenarios):

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

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

Many studies within our scope are regional (as opposed to global), making the link between the studied regional core system and planetary boundaries more distant and difficult to assess. For such studies, assessing the impacts on planetary boundaries requires extra hypotheses about the economic behavior of the rest of the world. This may explain why so few studies assess these impacts. For example, a German study may not assume a strong climate change because it would be equivalent to assuming that the other countries have not managed to reduce their GHG emissions enough. An EU study may not be willing to assess how critical lithium resource is in its scenarios because it would require to pose extra hypotheses about the transition in other regions of the world, about the global geopolitical context and so on.

**Recommendations to scenario producers**

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

- Endogenization or boundary condition: scenario producers should detail if the studied physical limits are endogenized in the model they used or if they are embedded in their boundary conditions. This choice should be justified with regards to the study strategy, availability of data...
- Methodology: scenario producers should make their boundary condition explicit and substantiate their choice for each scenario. Why was "2°C by 2100" selected for global warming hypothesis in the scenario?
- If the study is regional, narrative elements about the rest of the world should be provided to properly assess the impacts on planetary boundaries.

Justification should be provided if those limits are not considered, e.g. through a qualitative analysis detailing the potential impacts on the scenario of taking those limits into account, or to substantiate the absence of impact of taking them into account.

# III. Boundary conditions for the energy system are little justified with regards to their importance in driving the scenarios

In this section we provide discussion on the typical boundary conditions found in future studies. The boundary conditions are links between the considered core system and surrounding systems; as such, we often refer to other sections of our framework on the surrounding systems.

We also provide discussion about the links between the various boundary conditions. Boundary conditions must be consistent with each other through a consistent storyline (see section on future studies).

## A. Lifestyles and behaviors assumptions greatly drive energy, and power, demand

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

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

Lifestyles in interaction with the energy system also determine instant energy consumption (power demand), through daily behaviors. Hence some aspects of daily habits may have an importance on instant demand, especially for the power system: as electricity cannot be stored per se (unlike gas, oil, coal or uranium), power production must match power demand at any time. Hence if power demand is concentrated at particular moments, the power system supply-side must be sized to match demand at these high-demand moments (see power system operation).

As already discussed, many studies consider lifestyles and behaviors as boundary conditions, but other studies use a model which endogeneize them through economic processes. Section on energy consumption explains the different ways studies determine energy consumption in their scenarios.

**Recommendations to scenario producers**

Scenario producers should make their strategy about behavior changes explicit and justify if with regards to the study strategy. The following aspects should be considered:

- Endogenization or boundary condition: *which behaviors are modeled and which are assumed through boundary conditions?*
  - For modeled behaviors, the selected determinants of behaviors should be reported and justified.
  - For behaviors set by boundary conditions, a qualitative narrative should be provided to justify these hypotheses
- Consistency between the boundary condition and the whole storyline (policy framework, prices of fuels and materials…)

See the section on lifestyles for more detailed recommendations.

## B. Assumptions about technologies play a key role in scenarios

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

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

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

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

**The evolutions of technology prices (demand-side equipment or supply-side technologies) are also key drivers of the energy system evolution in scenarios**, especially for studies using models which determine the energy system through decisions based on prices, such as simulated agents models or benevolent planner models seeking costs minimization. As described in the following sections, prices of technologies may depend on prices of fuels and materials, as well as on labor cost (hence on place of production).

See section on supply for more details about supply-side technologies and section on consumption for more details on demand-side technologies.

As already discussed, the availability and technical / cost characteristics of technologies are the output of a part of the economic system: industries in these technologies and policies framing their activities (which are also boundary conditions).

**Recommendations to scenario producers**

Detailed recommendations can be found in sections on consumption and long-term evolution of the power system supply-side.

## C. In scenarios, demography is an uncontrollable certainty

Demography is a key driver of ESs, as it is a **key driver for demand**. In future studies, demography is a boundary condition for the energy system: no feedback is assumed from the ES to demography. Equivalently, demography is never endogenized, and never linked to the evolution of surrounding systems. Demography is determined through the storyline, and data are usually selected from demographic projections. Scenarios do not perform any sensitivity analyses on demography, which shows this variable is considered as suffering no uncertainty.

**Recommendations to scenario producers**

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

For each scenario within a study, scenario producers should substantiate the fact that demography is not affected by the proposed energy transition or by its impacts on surrounding systems. *Does climate change impact demography in the BAU scenario? Why?*

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

Political framework (taxation system and regulations/ standards) **affect individual behaviors as well as companies behaviors**. Hence it frames other boundary conditions.

Policy-making is never endogenized in future studies within our scope. Endogenizing policy-making would require to model it and link it to determinants. However, the goal of future studies is to influence policy-making processes. Thus the output of these processes need to be presented as possible choices, as opposed to be determined by various influences.

## 1. Tax system and public investments

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

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

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

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

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

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

**Public investments** are also a lever to foster the energy transition when public infrastructure need to evolve. For example, (Association négaWatt, 2014) proposes investment in public transportation; (ADEME, 2012) proposes to develop a finely meshed bike network in urban areas, which requires public investments.

## 2. Regulations and standards

Regulations and standards can lead to:

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

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

## 3. Social objectives and their policy equivalent

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

Studies using a benevolent planner philosophy perform some form of optimization or systematic method to reach an optimal point assuming these social objectives are reached (ADEME, 2012; Association négaWatt, 2014; Fraunhofer ISE, 2015; Barton et al., 2018).

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

**Recommendations to scenario producers**

Boundary conditions (if any) about taxation and public investment, regulations and standards, and social objectives should be explicit and justified with regards to the study strategy.

In case such boundary conditions are defined, the following aspects should be reported:

- Policy tools which are used
- Main effects of this tool

See section on lifestyles for more detailed recommendations.

## E. Prices of imported materials and goods are not considered in energy transition scenarios

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

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

Resources can be transported more or less easily, making them more or less global. Typically, if the cost of transporting a commodity is significant compared to the value-added contained in this commodity, the commodity will be exploited locally. For example, sand is a rather local commodity whereas high value-added goods (such as cars) are present on global markets.

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

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

The underlying assumption of making technology prices independent from import prices for goods and materials is that no significant evolution of these prices happens, in particular no shortage of materials and no geopolitical tension with exporting regions will happen during the scenario timeframe. In other words, this boundary condition may convey hypotheses about material criticality and the physical limits associated with it. Details on material resources criticality can be found in section on environmental assessment.

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

**Recommendations for scenario producers**

Boundary conditions (if any) about prices of imported materials and goods should be explicit and justified with regards to the study strategy.

In case such boundary conditions are defined, the following aspects should be reported:

- Evolution of the prices for each considered scenario and reasons why such an evolution was selected
- Narrative substantiating the described evolution, taking into account the global or local nature of the considered commodity: *why do prices evolve this way? Under what drivers?*
- Material criticality: *do these boundary conditions reflect material criticality considerations?*

## F. A very low diversity of assumptions about GDP evolution

**For some studies, GDP is an essential input which determines the aggregated demand level and hence is a key driver of consumption behaviors**[7]**,** determining in turn both demand and supply sides of the energy system. In other words, the GDP hypothesis represents how much the economy will grow in the scenario. **The GDP hypothesis ensures a consistency between consumption (in monetary value) and production (in monetary value) in the scenario**, representing the global ability to produce goods and services on the geographical perimeter.

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

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

"*Over the longer term the impacts of the [2008] financial crisis are projected to fade away, structural reforms start to yield results, labour markets improve and more supportive policies and financing conditions are projected to be put in place sustaining the growth in the EU Member States.*"

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

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

For example, the transformational scenarios of the European Commission' roadmap (European Commission, 2011) have the same GDP evolution as the Reference scenario (European Commission, 2016) following this line of reasoning:

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

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

[7] This is the case for studies using a GDP-based approach to determine energy demand, as explained in section about energy consumption.

This homogeneity across studies comes as no surprise as studies requiring to use GDP as an input are based on so-called IAMs (Integrated Assessment Models). These models have been originally designed as an answer to the World3 model from the Club of Rome and as such they assumed that a steady growth of GDP was a priority for human societies[8] (Nicolas, 2016). In other words, **these models are designed to have a steadily growing GDP as an input**: serious limitations could emerge under other hypotheses (such as their ability to inform about the desirability of transition or about the changes in lifestyles associated with such hypotheses). It comes as no surprise, then, that GDP hypotheses feeding them all look alike.

In fact, the GDP hypothesis sums up hypotheses about:

- Geopolitics of the world, such as the relative economic power of different countries: The usual hypothesis is that of slowly changing geopolitical situations. No geopolitical crisis is assumed, which might here again be considered as a collective blind spot for future studies.
- Hypotheses about the financial sector and its possible crises: The usual hypothesis is that no more crisis will happen during the scenario timeframe. Theoretically, the reverse hypothesis could also be selected for some scenarios in order to think such a possibility.
- Planetary boundaries, such as the feedback effect of climate change on the economy, or the possible effects of peak oil in the scenario geographical perimeter: **The usual hypothesis of a steady growth implicitly assumes that planetary boundaries are not significant determinants of the global economy during the scenario timeframe**. As already explained in I.B, this is largely questionable for "reference" scenarios leading to a significant climate change.

All these underlying hypotheses are largely unspoken. Detailing them leads to question the unity of GDP hypotheses across future studies. The low diversity of uncertain macroeconomic hypotheses has also been noticed in (Lezais, 2015) across future studies on transport.

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

**Recommendations for scenario producers**

Boundary condition (if any) about GDP should be explicit and justified with regards to the study strategy.

In case such a boundary condition is defined, the following aspects should be reported and justified:

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

## G. A very low diversity of assumptions about fuel prices

For European scenarios, (imported) fuel prices are considered as boundary conditions as the EU has no impact on them. **Data about their evolutions usually come from selected databases** produced thanks to world commodity models (such as the World Energy Model by IEA, PROMETHEUS by E3M, DECC 2050 Calculator by the

[8] Limits to growth, the report on the study using World3, claims that a global steady growth cannot be sustained up until 2050, because of the pollutions it would generate and a lack of resources on Earth (Donella H. Meadows, Randers, & Meadows, 2004).

United Kingdom (UK) Department of Energy and Climate Change). In some scenarios, a storyline is provided to explain prices evolutions. In other scenarios, they are considered as uncontrollable uncertainties, subject to sensitivity analyses.

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

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

**The evolutions of fuel prices described in future studies are key driver of the ES** as they partly determine demand structure (consumption level, demand side technology mix, final energy carrier) and the power system supply-side (through shifts within different fuels to produce power).

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

**Recommendations for scenario producers**

Boundary condition (if any) about fuel prices should be explicit and justified with regards to the study strategy.

In case such a boundary condition is defined, the following aspects should be reported and justified:

- Evolutions of fuel prices for each considered scenario and reasons why such an evolution was selected
- Narrative substantiating the described evolutions, in terms of global trends and volatility: *why do fuel prices evolve this way? Under what drivers?*
- Discussion about any significant difference between evolutions of prices in the real world and assumed prices: *In case price volatility is significantly different from what is observed in reality, what are the reasons for the change? What would be the impacts on the results of keeping the same volatility as today's?*

## H. Industrial offshoring pattern and industrial activity increase

### 1. Industrial trends have various important impacts on the energy transition

Industry represents a significant part of energy and electricity demands in EU (respectively 23% and 37% in 2016). On the long run, **offshoring patterns can significantly affect the energy and electricity system. They also affect the various impacts of the energy transition**:

- **Employment structure** is obviously impacted when an activity is offshored (a need for labor force disappears) or re-shored (new need for labor force).
- **Balance of trade** is also obviously impacted by offshoring patterns.
- **Costs of technologies** used in the scenario may be impacted by offshoring/re-shoring patterns, depending on the differences in wages levels in the considered countries. For example, if an industry producing a technology is offshored in a lower wages country, then the corresponding imported technologies are less expensive than technologies which were produced on-shore. In other words, offshoring patterns can lead to changes in technology prices, e.g. through using cheaper labor in less developed countries. This applies both for demand-side and supply-side technologies. However, to our

knowledge no scenario makes such explicit assumptions. The evolution of technologies costs are usually exogenous hypotheses in scenarios, based on learning rates projections or expert judgement, as explained previously.

- **GHG emissions**[9] associated with production processes spatially follow these processes when they are offshored: if steel production is offshored, then its GHG impacts are also offshored. This reduces the GHG emissions impact of the considered territory, but might increase or decrease the GHG impact at world scale. E.g, if the offshored activity is more carbon-efficient than when it was on-shore then the global impact is reduced (and the other way round) (Barton et al., 2018). See section on impact assessment.

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

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

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

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

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

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

In most cases, **scenarios do not provide explanations in their storylines about trend discontinuity in industrial activity**. However, the industry sector is very slow to change, in terms of physical infrastructures, which are long-lived[10], but also in terms of employees' skills and training. Also, industries evolve in an economic and institutional frame. Trend discontinuity in industrial activity might not be compatible with this frame. For example, relocation patterns in France may not be consistent with free movement of goods and capital between France and less developed countries.

To our knowledge, industrial offshoring and industrial activity increase are assumed as boundary conditions in future studies. Nos study endogenizes these patterns. The underlying assumption is that the energy system has no influence on them, even though energy prices may be a driver for offshoring (if it is too high) or re-shoring (if it low enough). Industrial activity is linked to other boundary conditions, such as the policy framework as compared to other regions.

**Recommendations to scenario producers**

Boundary condition (if any) about industrial offshoring pattern and industry activity should be explicit and justified with regards to the study strategy.

In case such a boundary condition is defined, the following aspects should be reported and justified:

- Trend discontinuity: if the industry offshoring or activity trend exhibits a sudden reversal (for example, a reindustrialization after ten years of offshoring), or trend discontinuity (e.g. offshoring patterns suddenly decrease), an explanation for this may be proposed: *does the economic and institutional frame driving industry behavior evolve in the scenario?*

[9] Or other environmental or society impacts

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

- Inertia of change: *how fast does the industry sector evolve? Does this change imply sunk costs?*
- Social impacts of offshoring, especially in terms of job transition desirability in the scenario geographical perimeter (also see section on desirability)
- Economic impacts of offshoring, such as on the balance of trade of the geographical perimeter
- Environmental impacts of offshoring: for example, offshoring may lead to actually greater GHG emissions if industrial processes outside the scenario geographical perimeter are more emissive. Such global impacts of offshoring or (re-shoring) should be made explicit in order to inform the consistency (or inconsistency) across future studies handling different regions. For example, if all national studies assume offshoring patterns, then they are not compatible taken together: no global impact assessment can be based on these studies (also see section on impact assessment).
- Consistency of this boundary condition with the whole storyline (policy framework, prices of energy…)

# IV. Boundary conditions for the power system are heterogenously justified

In this section, we focus on the power system (PS) and detail its specific boundary conditions. These boundary conditions may add up to the ones applying to the whole energy system, or they may integrate them in some ways.

## A. Interactions with other energy subsystems are mostly on the demand-side in scenarios, and increase electrification

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

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

**Energy needs outside the power system** (space and water heating, cooling, energy for transport etc.) **must be taken into account in order to include all the aspects of the problem**. Similarly, the other energy carriers aside from electricity should be considered, as well as the possible interconnections between networks and possible inter-conversions between energy carriers (especially storage) (Hache & Palle, 2019).

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

Interactions can be separated into two types of interactions:

- Supply-side interactions between carriers: these interactions consist in adaptations of the energy system's supply-side to convert one carrier into another. Examples include Power to $H_2$ through hydrolysis or Power-to-gas through hydrolysis and Sabatier reaction.
- Demand-side (indirect) interactions between carriers, through shifts between technologies using different carriers for fulfilling the same service. Examples include the shift from ICE cars to electric cars, or from gas heating systems to power heating systems.

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

**Recommendations to scenario producers**

Consistency between the sector scope of the study (in particular, which energy carrier is considered in the core system?), the carrier shifts proposed in the scenario and the driving questions should be substantiated. *For example, if a scenario proposes that mobility mainly switches to gas carriers and if the aim of the study is to assess the impacts of this change, then the study's sector scope should include the gas system.*

Scenario producers should check the balance during the scenario timeframe between energy supply-side and energy demand-side systems, for each energy carrier within the core system.

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

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

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

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

Scenarios make similar assumptions about these shifts:

- All transformational scenarios assume technology shifts within space heating systems, toward greater electrification: For France, (Association négaWatt, 2014) assumes a shift from heating systems based on oil or electric heaters to heating systems running on wood, electric heat pumps, micro CHP gas, district heat or thermal sun. (RTE, 2017) assumes a shift from oil to heat pumps. For UK, (Barton et al., 2013) assumes a massive development of heat pumps. Similarly, for EU, (European Commission, 2011) assumes a greater electrification of space heating. For water heating, it proposes shifts from gas boilers and resistance heaters to heat pump heaters or thermal sun heaters.
- Similarly, all scenarios assume technology shifts within the mobility sector (more commonly called mode shift), from ICE car to lower carbon modes (public transportation, bike…) or to hybrid car, electric car, CNG/LNG[11] car and so on. Most often scenarios assume a shift towards electric car, but a few exceptions exist ((Association négaWatt, 2014) propose a massive shift toward CNG/LNG cars).
- Some scenarios make assumptions about technology shifts within the industry sector, usually from heat processes (for compression or heating) to electric processes (Association négaWatt, 2014; RTE, 2017).

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

**These shifts impact the long term evolution of the power system both through different energy needs during the year and through different power load patterns** (the power at peak demand, or the time and duration of peak demand may evolve). For example, the electrification of mobility may lead to significantly greater peak demand depending on the management of the charging of batteries (EDF R&D, 2018; RTE, 2017).

**Recommendations to scenario producers**

Scenario producers should justify the evolution of power demand by describing the evolution of the carrier share and total demand on the demand side, through technology uses evolutions (see section on consumption).

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

[11] Compressed natural gas/liquefied natural gas

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

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

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

Supply-side interactions are included in point (ii). For the power system they are transformations from one carrier to electricity (through power plants, see section on long-term transition of the PS supply-side) and transformation from electricity to another carrier. The latter category includes power-to-hydrogen, and power-to-gas.

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

- Hydrolysis is performed to convert power into chemical energy stored under the hydrogen ($H_2$) form, through decomposing water. $H_2$ can be directly used by industry, or by fuel cell cars, or it can be stored and converted back into electricity via a fuel cell later (in this case $H_2$ is used as an electricity storage technology). Finally, it can be injected in the natural gas network (up to 30 % of the gas volume, representing 20% of the energy) and burnt with natural gas.
- Synthetic methane ($CH_4$) is obtained starting from $H_2$ and making it react with carbon atoms from carbon dioxide ($CO_2$) through Sabatier reaction. The obtained methane can be totally incorporated to natural gas. $CO_2$ can be obtained from CCS or from biogas purification.

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

Some scenarios give an extensive role to hydrogen, which totally replaces natural gas (Greenpeace, 2015). In other scenarios, hydrogen plays a power storage role (ADEME, 2015). (European Commission, 2011) uses it to feed the natural gas network and as a storage technology. Similarly, (SFEN, 2018) assumes the emergence of $H_2$ production from hydrolysis on the long-term (from 2050 to 2070), for injection in gas network and as a storage technology.

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

Other technologies or techniques to convert power into other energy carriers are mentioned by (EDF R&D, 2018), under the P2X concept. **P2X is the set of processes to convert power into another energy carrier which can be stored**: power to heat (P2H), power to gas (P2G), power to fuel (P2F), power to product[12] (P2P), or power to liquid (P2L).

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

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

[12] Hydrogen or gaseous hydrocarbons.

**Recommendations to scenario producers**

The technologies used to transform electricity into other carriers should be described, in terms of technical characteristics, costs etc (see section on long-term transition of the PS supply-side for more characteristics). The expected evolutions of these technologies should be detailed as should be the reasons for these evolutions.

## B. Interactions with neighbor power systems

The considered PS can be connected to other PSs through interconnections. **Interconnections participate in the power supply balance at any time by bringing more power (imports) or by evacuating extra power (exports) depending on the needs of the different interconnected regions.** Hence hypotheses about interconnections are important to understand the balancing capacity which will be available from interconnections in scenarios. These aspects are covered in this section. The sections about power system operation and long-term evolution of the power system supply-side mostly cover aspects of isolated power systems.

### 1. Interconnections: between solidarity and sovereignty

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

Other studies make assumptions about how the PS in neighboring regions evolve, such as (ADEME, 2015; ADEME / Artelys, 2018; Agora Energiewende, IDDRI, 2018; RTE, 2017). For example, pathways which might pose greater constraints for the French PS to ensure global security of supply than if no interconnection was available, are proposed in (RTE, 2017). This rationale **assumes solidarity with neighbor regions**, which directly questions the sovereignty assumptions made by the previous set of scenarios.

The sovereignty assumption is computationally simpler and requires less assumptions about neighboring power systems. However, in interconnected PSs, including the European one, market actors make decisions taking into account system wide information. RTE considers that in such a context, the sovereignty assumption is too simplistic and should be completed with extra-analyses to investigate the effects of this assumption (RTE, 2017).

The selected philosophy (sovereignty or solidarity) about interconnected regions is then translated into assumptions about interconnection capacities and evolution of the neighboring power system supply-sides, which are the subjects of the following paragraphs.

### 2. Simulating interconnections requires assumptions about interconnection capacities…

The scenarios simulating interconnections define hypotheses to compute the evolution of the interconnection capacities[13] and sometimes the implementation of new interconnection links. Here are the different approaches we observed among future studies to simulate the long-term evolution of power system interconnections, from the most rudimentary to the most complex, computationally speaking.

- (ADEME, 2012) directly assumes an extra power capacity always available in case of need to import, or export, power, through an aggregate capacity of interconnection.
- Some scenarios use results from inter-regional studies forecasting the evolution of interconnections in the considered region, such as (ADEME, 2015; ADEME / Artelys, 2018; Agora Energiewende, IDDRI, 2018; RTE, 2017). Some handle the uncertainty about interconnection evolution through sensitivity analyses. For example, (RTE, 2017)'s hypotheses are based on results of public studies about the evolution of the EU interconnections.

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

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

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

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

- As mentioned, (ADEME, 2012) assumes an extra power capacity always available in case of need to import, or export, power. However, this availability is assumed rather than checked through a modeling of, or assumptions about, the long-term evolution of the neighbor PSs.
- (ADEME, 2015) considers five regions interconnected with the French PS and assumes an 80% RES mixes for those interconnected regions. (ADEME / Artelys, 2019) considers the rest of the European PS as evolving as described in a future study by the European Climate Foundation, based on the Ten Year New Development Plan 2018 from ENTSO-E. In those case, studies assume as boundary conditions the evolution of interconnected PSs.
- Scenarios using PRIMES model for the European energy system make implicit assumptions about interconnected PSs in Switzerland, Norway and the Balkans, even though they are not part of the modeled energy market (E3MLab, 2017; European Commission, 2011; European Commission, 2016; SFEN, 2018). In PRIMES, from the point of view of each EU Member State, the mixes of neighboring countries are co-developed in an integrated way through market mechanisms.
- (RTE, 2017; RTE, 2018) assume three different pathways for the PS supply-sides in neighboring regions, including pathways which might pose greater constraints for the French PS to ensure global security of supply. Those pathways each integrate the interconnected regions into an economic model ensuring bankability of the different power generation technologies development.

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

## 4. Impacts measured through interconnections

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

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

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

**Recommendations for scenario producers**

A scenario strategy about interconnections should be defined and justified with regards to the study strategy.

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

- Hypothesis of sovereignty or solidarity. This hypothesis should be substantiated, especially if it requires evolutions from start year situation (e.g. for currently interconnected power systems the sovereignty assumption should be substantiated through a narrative, or extra analyses should be provided to show how the study's results would evolve if a solidarity hypothesis had been selected). *Is the studied PS independent of other, neighboring PSs? Is it fully connected to neighboring PSs with no means to control the interconnections?*
- Interconnected power systems and their evolutions: *which regions are interconnected to the studied PS? How do neighboring PSs evolve during the scenario timeframe? Why do they evolve in such a way?*
- Interconnection lines capacity: *how does the interconnection capacity evolve during the scenario timeframe? Under what incentives? Are new lines created?*
- Demand and supply instantaneous behavior of neighbor PSs (see section on power system operation for more details). *Have neighboring regions been simulated?*
- Impacts: the strategy about impacts associated with power imports/exports in the results, for each impact which is considered in the study (e.g, GHG emissions) should be described (see section on impact assessment for more details).

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# The Shift Project

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

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