Long-term evolution of the power system supply-side in energy transition scenarios

Technical file #6 – Draft version

Information and recommendations for scenario producers

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

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

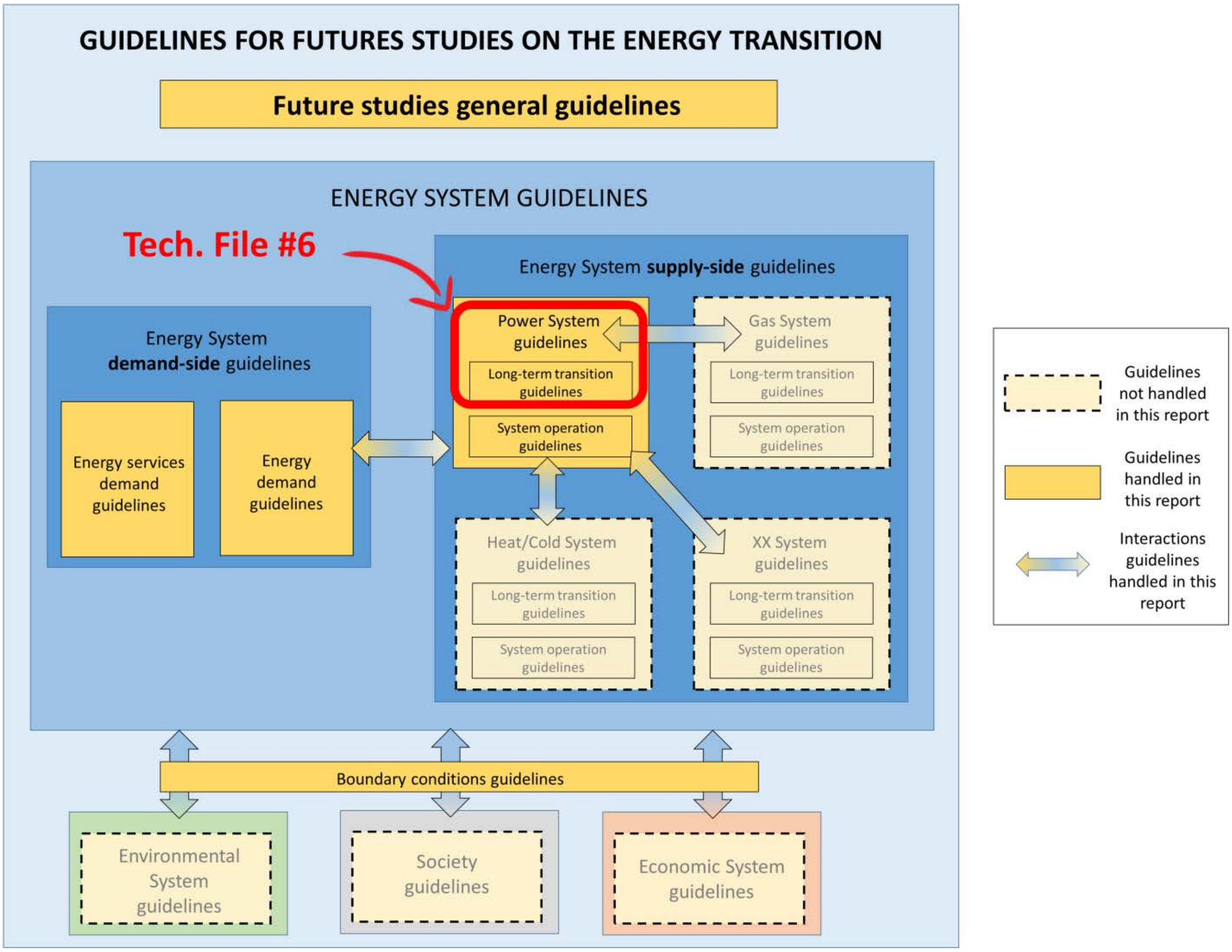
The goal of this project is to produce a set of guidelines addressed to scenario producers. These guidelines seek to **foster transparency and consistency *within* future studies** and to **develop a common language *across* studies**. By defining a number of important items which are key to deal with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

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

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

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

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



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

We warmly thank the experts who participated in this project by putting forward ideas and critiques, references and documents, and who accepted to discuss these ideas with us and other experts:

- Alexandre BARRÉ (UFE)
- Alain BELTRAN (Fondation EDF)
- Nicolas BERGHMANS (IDDRI)
- Michel BERTHÉLEMY (SFEN)
- Christophe BONNERY (ENEDIS)
- Sandra BOUNEAU (Institut de Physique Nucléaire d'Orsay - Université Paris Sud)
- Anne BRINGAULT (CLER-RAC-F)
- Julien BUEB (France Stratégie)
- Alain BURTIN (EDF)
- Jean-Michel CAYLA (EDF)
- Michel COLOMBIER (IDDRI)
- Emmanuel COMBET (ADEME)
- Patrick CRIQUI (Laboratoire d'économie appliquée de Grenoble)
- Dominique DRON (Ministère de l'Économie et des Finances)
- Robin GIRARD (Mines ParisTech)
- André-Jean GUÉRIN (The Shift Project)
- Emmanuel HACHE (IFPEN)
- Sylvain LASSONDE (Université Paris Saclay)
- Tanguy LE GUEN (ENGIE)
- Robert LOWE (University College of London)
- Arnaud MAINSANT (ADEME)
- Nadia MAÏZI (CMA)
- Teresa MADURELL (Institut de Ciències del Mar, Barcelona)
- David MARCHAL (ADEME)
- Yves MARIGNAC (Association négaWatt)
- Solange MARTIN (ADEME)
- Chloé MEXME (ENEDIS)
- Gilles MITTEAU (Chaîne Youtube Heu?Rêka)
- Thomas PELLERIN-CARLIN (Institut Jacques Delors)
- Jacques PERCEBOIS (Université de Montpellier)
- Dimitri PESCIA (Agora Energiewende)
- Gondia SECK (IFPEN)
- Laurent SCHMITT (ENTSO-E)
- Damien SIESS (UFE)
- Vera SILVA (GE Renewable Energy)
- Jordi SOLE (Spanish National Research Council, Madrid)
- Philippe TORRION (anciennement EDF)
- Eric VIDALENC (ADEME)

We also warmly thank the benevolent Shifters who helped us for the research for this technical file: Damien Ambroise, Sacha Bentolila, Fahd Boukrouche, Anne-Laure Delaye, Julien Kelder, Clément Le Priol, Arnaud Leroy, Alzargal Murat, Gaspard Pena Verrier, Félix Veith.

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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. The power system and its architecture

A. The power system is highly complex and intricated in our daily lives

(Véronique Beillan, Caroline Bono, Sophie Bouly De Lesdain, & Fabien Bricault, 2018) describes how a PS is composed and proposes an overview of how it works. Here are the main points which are developed to better understand PSs.

The PS is probably the greatest industrial system in the world. It must be available 24/7, immediately, and must remain invisible for most consumers. The PS could be described through a multi-layer structure:

- A physical network which follows the rules of physics
- Instant balance between produced energy flows and energy consumption must be kept at all times
- A variety of actors act on the PS following the market rules
- The whole system requires an information technologies layer to properly operate

1. Consumption of electricity reflects a country's activity

Since the beginning of electricity use, the volume of electric energy which is consumed annually grows continuously. Depending on the evolution of other energy carriers (oil, natural gas, etc, see boundary conditions section) and on economic conditions, this growth has been fluctuating.

When speaking about electricity consumption, Whatt-hours (Wh) are often used; for large, national PSs, Twh/yr are used; for electricity bills, kWh are used.

But this is only one aspect of electricity consumption: consumption is dynamical, it evolves permanently. It directly reflects our own activities, and even the activity of a whole country.

It ranges from lighting in dwellings to ovens, electric radiators, washing machines, dryers, vacuum cleaners and so on. Smaller consumptions like mobile phone charging are also counted in.

In addition to these residential uses, tertiary and industrial activity is taken into account, including fabrication processes, steel production, and goods transportation.

Consumption permanently evolves, following a time pattern which is driven by our lifestyles:

- The **night break**: it is the moment when global activity (both industrial and residential) is the weakest, so electric consumption is the weakest too.

- The **morning load rise**: it the moment when a country "wakes up". Inhabitants actually wake up, public transportations start operating, people arrive at their workplaces and economic activity starts; heating systems, computers, lighting, are turned on.

- Then a consumption decrease is observed from noon (breakfast) until a minimum consumption point called **the afternoon break**.

- The end of workday corresponds to another rise in electricity demand. People stop working, go back home, may do the groceries and prepare dinner. At this time, transportation is greatly used (as in the morning), shops, supermarkets are much visited; cooking devices, TV sets, lighting (for shops, public places and dwellings) are turned on. All these activities and uses correspond to the **evening peak**, around 7pm.

- Activity decreases for the night and correspondingly demand strongly decreases. During the evening and the night, little consumption peaks corresponding to the automated start of specific equipment such as electric water heaters can be observed, following tariff signals.

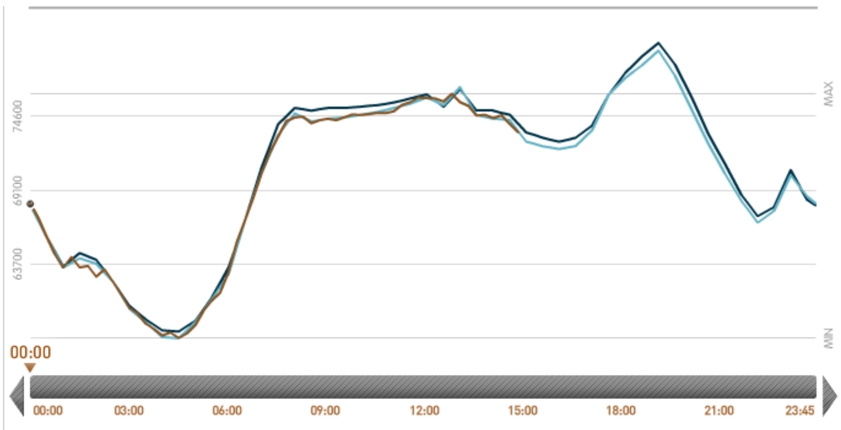


Figure 1: Source éCO2mix, RTE

This type of consumption curves (called load curves) finely reflects a country's activity. As a consequence, the following characteristics can be observed on time scales larger than the day:

- Workdays follow each other, being very similar to each other
- Weekend days are different than weekdays
- Public holidays and vacation periods have specific characteristics
- Winter demand does not have the same shape as summer demand: in summer, longer days require less lighting or heating, etc.

Depending on the country, electric space heating can represent a large share of total heating. The greater this share, the more electricity demand depends on outside temperature. A sensitivity of demand to temperature is observed. This is particularly true in France for example, but other EU countries have a lower sensitivity. Some countries even display the opposite pattern, with a summer peak due to massive air cooling during hot days.

2. A wide variety of generation technologies in two categories: those producing alternative current (AC) and those producing direct current (DC)

Electricity production is a matter of energy conversion, from a primary energy (coal, uranium, gas, wind, sun rays…) to electric energy.

Numerous processes exist, but they do not have the same efficiency nor the same cost, which is important when it comes to large-scale electricity production.

Primary energies which are used to produce electricity are the following:

- Mechanical energy (the most used primary energy to produce electricity, through the work of an alternator)
- Photovoltaic energy (PV), which is booming
- Thermoelectric energy
- Electrochemical energy (used in batteries and power cells)

Electrical current can be produced under a continuous (Direct Current, DC) form or an alternative form (Alternative Current, AC).

Two types of power production units can be distinguished:

- Those which directly produce alternative current. The current is directly injected on the grid through an inverter. The following technologies belong to this category: thermal power plants (using coal, natural gas, oil, uranium to produce heat), hydropower, tide power, concentrated solar power (CSP), geothermic heat…
- Those whose production must pass through a power electronics device (a converter) to be injected on the grid. Most of the "new" renewable plants, called Variable Renewable Energy Sources (VRES) belong

to this category: wind turbines, photovoltaic panels (PV), wave energy technologies, marine current technologies…

3. The grid is the infrastructure for transporting energy from production points to end-consumers

The grid is the physical link between production and the millions of final consumers, would they be individuals, industries or state agents. The grid is composed of numerous technical equipment. Its structure is highly complex.

PS are characterized by several physical values:

- Voltage is expressed in Volt (V). It is similar to the pressure, in a water pipe system.
- The current is expressed in Ampere (A). It is similar to the flow of water, in a water pipe-system
- Power is expressed in Watt (W). It is equal to voltage x current
- Energy is expressed in Watt-hour (Wh). It is equal to power x time
- Frequency is expressed in Hertz (Hz). This value is useful only for alternative current. It represent the speed at which current and voltage waves beat.

These values can be computed everywhere in the PS thanks to well-known physical laws and the fine knowledge of the system components.

In order to connect large production stations to end consumers, the grid is structured in several layers. Those layers correspond to different voltage levels. They have complementary functions.

- Transmission network is responsible for allocating the energy to the different regions. It is the "highway" network of electricity. Large power plants are connected to the transport network. It is also responsible for exchanging the electricity between countries, through interconnexions.
- Distribution network is responsible for bringing the energy from the transmission network to end consumers (industries, companies, households). This is the "small road" network of electricity. Smaller production plants are connected to the distribution network.
- Transborder interconnexions are physical links between PS of different countries. They enable the exchange of energy between them and hence they are support for economical exchanges.

a. Transmission grid

The transmission grid has a structure which is designed to ensure a sufficient security of supply by finely interconnecting regions so has to communalize emergency capacities.

Transmission transformers are the nodes of the transmission grid. They have several functions:

- Transforming electricity from a given voltage level to another, within the transmission voltage levels.
- Allocating electricity thanks to bar sets, and disconnectors (FR sectionneurs)
- Controlling and protecting the PS (control system, sensors, circuit-breakers (FR disjoncteurs))

High-voltage lines are the links between the nodes. Electricity travels through them.

They are mostly open-air lines. Air ensures the isolation between the line and the ground. Lines are produced in conductive material; they have a low resistance but still get heated by the electric current they transmit. As every metal which warms up, they get longer and get closer to the ground. In order to avoid any electrical contact with the ground, the amount of current (intensity) should not be too high.

b. Distribution grid

Source transformers are the nodes linking the transmission grid to the distribution grid. They are in charge of lowering the voltage for the distribution grid. They also participate in the control and protection of the PS.

The structure of the distribution grid is designed to distribute electricity to end-consumers (tree-shaped), with some actuators enabling a certain degree of control over the topography of the grid.

B. The architecture of the PS

1. The larger a PS, the cheaper and the more secure

Historically speaking, PSs used to be located around "sectors", that is, groups of companies and housings which consume electricity. Gathering the different groups into larger electrical regions and further into national electrical regions was soon found economically interesting. This enlargement was further extended to continental regions, e.g. with the installation of high voltage interconnexions between European countries (Véronique Beillan et al., 2018).

There are three reasons why larger PSs are more efficient:

- Economies of scale for production units can be obtained when a large group of consumers is gathered, as production units can be larger.
- Linking the production capacities enables a better reaction to contingencies on production or consumption with the same total capacity.
- The aggregation effect. The linking of production (or consumption) units through a meshed grid leads to an aggregated production (or respectively consumption) whose random fluctuations are statistically reduced (that is, their sum is rarely zero nor the maximal sum). In other words, a wind farm production is much more variable than the aggregate production of all the wind farms of a country; demand from one town is much more variable than the aggregate demand of a country. This effect is illustrated by data measured for a week in France from onshore wind (see Figure 2): at the farm level, variability is high; at the aggregated regional level, variability is lower, and at the national level it is even lower. Also, several different production technologies may complement each other (hydropower stations and thermal stations have different characteristics which are best used in complementarity). These effects enable to benefit from the complementarities between load curves and between production capacities.

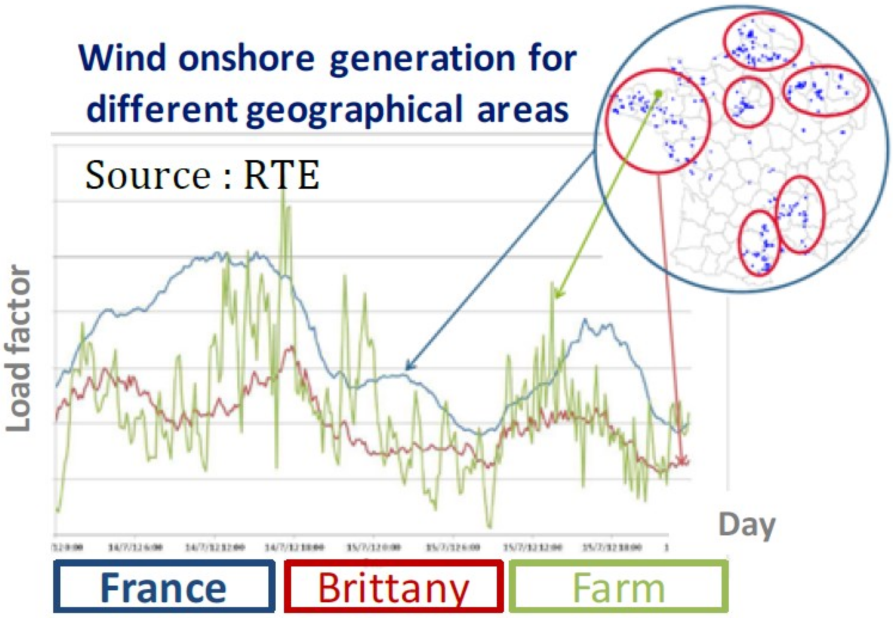


Figure 2: onshore wind generation for different geographical areas in France (EDF, 2015).

Beyond its size, the PS can theoretically have different physical architectures, from highly centralized (which is currently the case in European countries) to highly decentralized.

2. The scale at which the PS is driven greatly determines its structure

Several authors link the physical architecture of the PS to the decision levels which drive its evolution (Foxon, 2013; France Stratégie, 2017; Véronique Beillan et al., 2018).

Indeed the PS can be driven by a variety of scales:

- It can be driven by local decisions. For example, individuals can decide to be power producers through PV; neighborhood dwellers can be involved in an eco-district project with local and national companies, or they can invest in wind power through local crowdfundings; conurbations can define the evolution of their power system through local energy plans.
- Regions can also define power system evolutions (such a trend is re-emerging in Germany (France Stratégie, 2017)).
- Decisions can be taken at a national or supra-national level (as evolution strategies for EU interconnections (ENTSO-E, 2015)).

(RTE, 2017) observes a trend in France towards PV self-consumption by individual households and shows this trend has potential effects on economic flows between agents (individuals, electricity providers, system operators (TSOs and DSOs), the State and territories). Hence aspects of the PS architecture are driven by individual decisions, the remaining aspects being driven nationally.

(ADEME, 2014) points out that local resources in terms of heat, biomass, renewables as well as local needs (depending on the local climate) should be taken into account for a better energy system design. Methodologically speaking, in this study the local thinking is performed at the energy system level, whereas the PS architecture remains centralized at a national level, with more individual self-consumption though. This is also the approach followed by (ADEME, 2015). Here again, some aspects of the architecture of the PS are driven by individual decisions, the remaining aspects being driven nationally. However, no clear overview of the PS architecture is proposed in those studies.

(Association négaWatt, 2014) notes the limitations of self-consumption depending on the type of urban fabric: in dense urban areas, PV self-consumption is not viable because the PV surface per inhabitant is too low. On the contrary, in rural areas, too much would be produced per inhabitant, but distribution network could not handle this production except if heavy investments are done to reinforce it. Hence this scenario keeps a centralized approach for the PS, driven by national decisions.

(Foxon, 2013) argues that the type of actor driving the PS evolution is the key to understand its emerging architecture. Their pathways are articulated around three different types of actors: the central government, market actors, and civil society. In each pathway, one of these actors clearly dominates the debates and drives the PS evolution. Because these actors have different interests and views about the energy system, the resulting PS architectures are different.

- The government logic is to directly co-ordinate the energy system in order to reach policy goals such as being a global leader for some technologies enabling future technology transfers and benefits to UK industry. The top-down management of the transition leads to a highly centralized PS;
- the market logic is to let market actors interact freely within a high-level policy framework (such as a carbon tax, or an emissions trading scheme). Under industry lobbying, the UK government provides support for large-scale low carbon demonstration and commercialization (CCS, offshore wind), also leading to a highly centralized PS (coal and gas with CCS, nuclear, offshore wind);
- the civil society logic is that local actors take a leading role in the decisions about the energy system in order to meet the needs of local citizens. Partnerships between local authorities, housing associations and energy companies lead to energy efficiency of existing building stock, local district heating systems in urban areas, more local investments, domestic and non-domestic distributed generation options. Large industries keep on focusing on nuclear and gas and coal with CCS. This decision patterns leads to a partly decentralized system, backed by centralized elements.

3. Highly centralized, highly decentralized and mixed architectures

(France Stratégie, 2017) investigates the possible PS architectures by imagining three different extreme architectures: totally centralized, totally decentralized, and mixed.

- The totally centralized PS is very similar to the one existing in France. It is based on a transmission and distribution network ensuring the proper supply demand balance without storage technologies, and enables equity between all the consumers connected to the network through a unique national price of electricity. This type of PS can host large shares of VRES if it keeps back-up plants such as new nuclear power or gas and coal with CCS.

- The totally decentralized system is composed of autonomous PSs ruled by cities, neighborhoods or citizens' organizations. It is based on small-scale renewables and inter-season storage technologies and requires some form of solidarity within territories. In this system, equity is difficult to ensure across territories. Consumers need to adapt their demand to variable production, with the help of microgrid information systems and through significant behavior changes.

- The mixed PS is based on a decentralized PS backed by a centralized PS to ensure a high security of supply and transfers between microgrids. Its drawback is the high requirement in investments in order to develop and maintain both systems.

To the best of our knowledge, no future study proposes a totally decentralized PS.

The concept of PS architecture is particularly important to consider as it drives issues of capacity and flexibility sharing between territories as well as the amount of investment required to implement the architecture.

4. Two architectural dimensions: physical and functional

We can distinguish two aspects of the PS architecture: its physical architecture and its functional architecture.

The physical architecture refers to the different pieces of equipment, plants, elements of grids, and their precise location in space and physical links between each of them. Physical architecture can be much centralized with a few large-scale generation plants only (RES or not) and electricity going one way to consumption spots. On the contrary, it can be much decentralized with numerous small-scale generation plants (RES or not) and electricity flowing both ways in the grid.

The functional architecture refers to the way information flows to control the PS. This architecture can be centralized with a global control being performed, no matter the physical architecture of the PS. For example, a global control of interconnected micro-grids with local storage capacities could be proposed in a scenario. On the contrary, the functional architecture can be decentralized, decisions about how to control the PS being taken at a small scale with decentralized intelligence. A decentralized functional architecture could happen around large-scale generation plants, or around micro-grids within a decentralized physical architecture.

Recommendations for scenario producers

Scenarios should include considerations on the PS architecture in their storylines or results. In doing so, the following aspects may be developed:

- Type of physical architecture of the PS: is the PS architecture centralized, decentralized, or mixed? What are the decentralized components of the architecture?

- Type of functional architecture of the PS: Is the PS centrally controlled? Are some elements of the PS partly autonomous from other parts of the PS?

- Actors driving the transition of the PS architecture, and their reasons to drive it this way

- For new types of architectures: analyses of PS security of supply, costs assessments, energy inequities…

II. The evolution of the power system's supply-side in scenarios

A. The drivers of the evolution of the PS supply-side

Scenarios use different approaches to model the evolution of the power-supply side system over the scenario timeframe.

They usually use a one-year time resolution to model the decisions around this evolution, and/or to model the corresponding evolution, more rarely five-year time resolution.

Decisions are made about the evolution of the power capacity, the evolution of the power generation portfolio, the evolution of the grid, the evolution of storage and the evolution of demand flexibility.

Based on the scenarios we studied, we could distinguish two different methodological axes discriminating studies. The first axis is the way time is integrated into decision-making in the model. The second axis is about the specific rules followed in the model when making decisions about the evolution of the PS supply-side.

1. Decisions about the PS supply-side evolution are differently grounded in time in different future studies.

In the different future studies we reviewed, we could distinguish two main different approaches regarding how decision-making relates to time: the time-based approach and the intertemporal approach.

In the **time-based approach**, time is simulated through time steps. At each time step, decisions are made about the power supply-side system, making it evolve (see Figure 3). Decisions are based on what happened at the previous time steps. Models such as POLES (Keramidas, Kitous, Schmitz, European Commission, & Joint Research Centre, 2017), used in (DGEC/CGDD/ADEME, 2015), or the WEM (International Energy Agency, 2018), used in (OECD/IEA, 2017) have this approach.

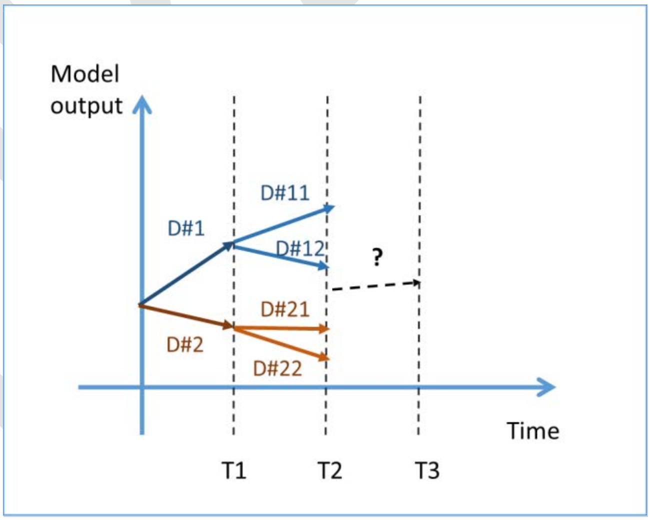


Figure 3: In the time-based approach, at each time step decisions are made by the model to drive the power supply-side system towards a direction. In this diagram, the possible decisions are represented by arrows and are numbered by D#xx. Of course, over the course of a simulation only one path is selected.

In the **intertemporal approach**, decisions are made about the power supply-side system based on a perfect knowledge of all the events happening during the scenario timeframe. In this approach, time is not simulated per se. Instead, some optimization rules are applied over the whole trajectory within the time frame. Some models' documentations talk about "perfect foresight." The intertemporal aspect is more accurate: decisions are made on the total trajectory rather than at "time steps". Hence it is not useful to talk about perfect foresight, because it implies that time-steps are sequentially simulated and that decisions are made at each of them, which is not the case (see Figure 4).

However, some constraints linked to time are represented in the effects of the decisions: power plants and other power installations are tracked and have a lifetime; some constraints on the maximal amount of installations that can happen in one year can also be applied. In other words some inertia can be implemented in the model, constraining the intertemporal decision of the model to some trajectories and excluding the trajectories which do not respect the inertia constraints.

Most of the studies use this approach to drive the PS supply-side. This approach could be called a trajectory designer approach. It may seem less realistic than the time-based approach, but actually the driving questions to which the scenario producers want to answer may justify such an approach. Basically, the goal of future studies is to inform possible pathways and their various implications beforehand, so it may come as natural to take the comfort of globally envisioning the transition to make it more coherent and smoother, sometimes at the expense of understanding and concretely explaining why one decision was made at a given point in time in a scenario and not in another one.

Figure 4: In the intertemporal approach, decisions are made by the model about whole trajectories, as opposed to decisions at each time step.

2. Future studies use different rules to drive the power system supply-side evolution.

We distinguished three different rules driving the power system supply-side in the future studies we reviewed: the cost-optimization rule, the portfolio rule and the preference rule.

a. Cost-optimization rule: the PS supply-side is driven by costs considerations

The **cost-optimization rule** drives the power mix by adding up costs involved along a transition pathway, usually under the form of a total system cost with a social discount rate (see section on economic evaluation) and applying a minimization function to it in order to find the least-cost pathway.

Cost-optimization models are used to apply this rule. These models always use the intertemporal approach, as their goal is to make decisions over whole trajectories (find the least-cost one).

Cost-optimization models are most often working on the PS supply-side only. Hence they require an exogenous power demand trajectory. This is the case for Artelys Crystal (ARTELYS / European Commission, 2017) used in some ADEME studies (ADEME / Artelys, 2015; ADEME / Artelys, 2018) and in (Agora Energiewende, IDDRI, 2018).

The power system module of PRIMES model (E3MLab, 2017) is also a cost optimization model requiring an exogenous power demand trajectory. However, this module is connected to an energy demand module[1] through electricity prices obtained over the trajectory to satisfy electricity producers. Prices affect the demand trajectory

[1] Also see the consumption section.

through different consumption decisions from individuals and companies, and the new trajectory is injected back in the power system module, and so on until this process converges to a trajectory satisfying electricity consumers and electricity producers.

Concretely in these supply-side models, mathematical tools such as Levelized Cost of Electricity (LCOE, called i-LCOE in the economic evaluation section) are used to compare the different competing technologies and decide which mix will be implemented.

Some constraints apply to these minimization choices based on LCOE, usually constraints of minimal security of supply, or similar proxies, for the overall PS. Some other constraints are included in the costs, such as a carbon price.

By taking into account these constraints, the power mix ends up to gather several different technologies rather than the most economic one based on pure-LCOE decisions. If decisions were taken only considering the LCOE of technologies, then the technology with the lowest LCOE would systematically be selected, and the mix would end up with this only technology. This is due to the fact that LCOE does not inform about the future incomes from power sales. In reality, if only one type of technology were installed in the power mix, security of supply would decrease because peak load would not be satisfied, or because fast reserves (FCR, see section on PS operation) would not be large enough in case of event, or because other anciliary services would not be provided.

Models incorporate these constraints by equations checking the proper operation of the power system on an hour by hour basis. This check can be performed with more or less complexity, taking into account several years of weather, simulating weather chronicles; in these checks the weather affects power generation (especially wind turbines and solar panels), but can also affect power demand; also, reserves can be simulated (see below).

A few models optimize conjointly the PS demand-side and supply-side. This is the case of REMod-D-TRANS model used by (Fraunhofer ISE, 2015). This model cannot use linear optimization methods hence instead of using LCOEs it explores a great number of different energy systems and compares their total system costs (see section on economic evaluation) in order to select the one with the lowest cost, without being sure it is the absolute minimum cost.

Note that the cost-optimization rule is sometimes considered by economists as the emerging behavior from "perfect markets". Hence some of the studies using this rule might use narratives about entrepreneurs making decisions instead of a benevolent planner following an optimization rule.

Such studies depicts decisions as if they were made by investors and entrepreneurs in the electricity domain. Indeed, investors are simulated through a "cost of capital" by which they are remunerated for their investing their money in power supply-side systems. Entrepreneurs make decisions to launch projects in such or such power industry taking into the costs they will face (including capital costs) and their expected electricity sales, which can be approximated by LCOE. For example, PRIMES considers its power supply module models "stylized companies aiming at minimizing costs" with a "perfect foresight". The Bilan Prévisionnel 2017, without being clear about the rule it follows, also claims to model investors and entrepreneurs, and distinguishes them for each power generating technology through different remuneration rates depending on the associated risks to invest in this technology (RTE, 2017).

b. Portfolio rule: the PS supply-side is driven by traditional good practices to design centralized PS

Portfolio rule builds up the power mix using "rules of thumb" to decide which technologies to add in the existing mix. The goal of these rules is to get a secure system favoring a variety of technologies without necessarily being the most cost-optimal mix of technologies.

POLES model applies such a rule: it considers different blocks of power production needs depending on the duration over which they happen during the year[2]. For each block and each year, if generation capacity is missing,

[2] Similar to the traditional distinction between base load, semi-base load and peak load but with mode load categories

technologies competes on cost considerations to fill the lack, through a technology portfolio selection process[3]. This process results in a portfolio of technologies within each block of production needs (Keramidas et al., 2017). The WEM proceeds in a much similar way[4] but selects the technologies based on a cost indicator which includes information about the flexibility and ability to provide power at times of high demand[5] (International Energy Agency, 2018). Typically, grid evolution due to the growing demand and due to the selected technologies is considered as a by-product of the mix: grid costs are not considered in the selection process for building the mix.

This rule, as it is based on filling up a gap between demand and already built generation capacity, is always applied in a time-based decision approach: at each time step, the gap is measured considering the capacity which was built or which reached the end of its life in the previous time steps, leading to the decisions. Hence this rule easily fits in econometric models[6] such as POLES and WEM, which cover larger geographical areas (EU, or the world), but which are less technology-rich on the demand-side, than models using the cost-optimization rule. The portfolio rule is based on "traditional" good practices for designing a centralized PS supply-side, which have been efficient to ensure security of supply (such practices are described and discussed in (IRENA, 2017)). Hence the amount of calculation required to apply this rule is lower than a full cost-optimization with security of supply constraints. This is why this rule is more adapted for larger geographical scopes.

Here again, note that this rule could be considered as simulating the behaviors of investors and entrepreneurs.

c. Preference rule: the PS supply-side is driven by an overall storyline

Preference rule builds up the power mix based on a selected storyline which sets overall preferences for driving the power mix. For example, négaWatt studies use a sobriety / efficiency / renewable energy preference rule to drive the energy system and the power system (Association négaWatt, 2014; Association négaWatt, 2017).

Some transition scenarios for UK have been designed imagining dominant actors would govern the power system evolution (Barnacle, Robertson, Galloway, Barton, & Ault, 2013; Barton et al., 2018; Boston, 2013; Foxon, 2013; Hammond, Howard, & Jones, 2013; Hammond & Pearson, 2013): in the Market Rules pathway, the energy system is governed by liberalized and electricity markets as is currently the case; in the Central Co-ordination pathway, the energy system is governed by a central government agency; in the Thousand Flowers pathway, the energy system is governed by civil society. A panel of stakeholders have been invited to directly propose mix evolutions that would fit those different narratives. Finally, a power system model has been used to adjust the obtained power mixes by adding "back-up" capacity, that is, highly flexible and dispatchable power plants.

The Roadmap proposed by ECF explores the conditions to reach pre-defined power mixes. As such, the study sets up preferences towards a few power mixes (deeply decarbonized ones) by forcing the share of energy produced by such or such technology in 2050. The model used then determines the cost-optimal capacity mix which is able to produce this energy (ECF, 2010).

This rule is partly manually applied, partly applied through computational models. It is probably more applicable in intertemporal approaches, as the preferences usually apply to the whole trajectory rather than change at each time steps.

Recommendations to scenario producers

Scenario producers should describe the rule they use to drive the evolution of the PS supply-side in their study. They should explain why such a rule was selected with regard to their driving question(s) and study strategy.

For each rule they should be transparent about the following aspects:

[3] The more costly the technology, the lower its share in the selected portfolio. Limitations are applied for the participation of each technology in each block. For example, peak production cannot be fully covered by variable renewables. Storage technologies other than pumped hydropower are not considered.
[4] Even though it is not clear in the documentation, the portfolio seems to be selected based on some distribution function (Weibull, or logit) such that technologies with lower cost indicator are more present in the final generation mix. The latest WEM (2018) claims to include power storage technologies without providing any detail about it.
[5] They call this indicator the VALCOE, for Value Adjusted Levelized Cost of Electricity.
[6] These models make decisions through a time-based approach, each time step being influenced by the previous ones, notably through elasticity links between consumption and prices. These elasticity links are econometrically measured and are always relative links: "if price increases by x%, then demand decreases by y%."

For studies using the cost-optimization rule, the following aspects should be reported about:

- the cost perimeter, that is, all the cost elements included in the objective function should be mentioned.
- The macro perimeter (supply-side only or whole PS) of the optimization should be mentioned.
- Elements outside the objective function whose cost could significantly evolve between scenarios of a same study. For example, if demand-side is significantly different between two scenarios whereas the objective function has not included demand-side, the results of the optimizations should not be compared.
- Method used to translate LCOE hypotheses into decisions
- Sensitivity analyses on LCOE, especially changes of LCOE ranking: cost-optimization problems are highly sensitive to cost hypotheses, hence this question should be considered. Not considering it should be substantiated: *why is uncertainty on technology relative costs not considered?*

For studies using the portfolio rule, the following aspects should be reported about:

- The technologies participating in the technology portfolio selection process: *are storage technologies taken into account?*
- The selection process: *how is the portfolio designed? What criteria are used?*
- Grid evolution rules, and their place with regards to the technology portfolio selection process

For studies using the preference rule, the narrative(s) driving the power supply-side evolution should be provided. In other words, the different decisions which explain the evolution should be substantiated.

B. The technical components of the PS supply-side with transparency tables

In every scenario, a set of technologies is available for the construction of the supply-side mix. This list, as well as the characteristics of each technology, differ from one study to another. In an attempt to improve comparability between studies so as to foster a participation in a common effort, we present here five tables that can be used by scenario producers.

NB: As developed later, **these tables are not to be "completed"**. The idea is rather to simply transfer the **already-existing** study information (in the form of a value, or a reference to the paragraph dealing with the given characteristic, etc.) in order to **centralize** them in a transparency effort. Therefore, only a part of columns and boxes may be concerned by a given study, the others remaining empty.

The five tables are divided as follows: two tables of technical characteristics (for production units and storage units), and three tables of economic, environmental and social characteristics. The technical and/or economic characteristics are usually those used in the construction of the scenario supply-side mix. Environmental and social characteristics are more commonly used to measure output impacts, but they may also be an input criterion in the same way as other characteristics (e.g. environmental criteria could be used by a benevolent planner to build the power mix).

We have tried to be exhaustive in the characteristics, but scenario producers may want to complete these tables by adding columns where necessary.

1. Objective of the proposed tables: promote transparency so as to foster a common effort in future studies about the energy transition

Each future study defines a set of technologies that can be used to build the supply-side mix. Once these technologies have been defined, the technical characteristics of these technologies may vary from one scenario to another for different reasons:

- The data sources and assumptions used are numerous. Thus, two different studies may use different values for the same characteristic of the same technology.

- For the same technology, the input characteristics (exogenous data) used to determine the mix are not always the same. Thus, two different studies may use different characteristics for the same technology.
- The level of granularity in the list of technologies available in each study may be different. For example, depending on the studies, it may be possible to define a single PV technology, or to distinguish between ground and roof PV, or not to consider this technology at all.

Therefore, it may be important to **bring some clarity** to these specific aspects. As explained in the general introduction (see corresponding part), the goal of the Power Systems 2050 project is **twofold**: sharing **best practices** so as to give scenario producers the opportunity to benefit from them and proposing tools allowing them to adopt a **common "language"** so as to foster a common effort. The 'transparency tables' proposed here primarily aim at addressing this second aspect: **facilitating inter-study comparison**. Our goal is that scenario producers who wants to participate in this common effort use this tables which could be a shared standard for greater transparency. As developed in the Future studies section, transparency is key to foster a dynamic and lively scenario community and, with it, the health of the energy transition debate.

To this end, the idea is simply that scenario producers report in these tables the information **used in their scenarios**. Thus, for any given study, many boxes and columns will remain empty because they do not use these characteristics. The goal is **not** to fill the tables completely. This is a way of visualizing information, of **understanding which characteristics are useful for a study and which characteristics are not**. Again, this depends on the driving question and the study strategy to answer it (see Future studies file). For this reason, each characteristic may either not be used in a scenario, be an exogenous assumption of a scenario, or be an endogenous result depending on the study. In any case, the information is interesting when trying to use the work of several studies (compare, combine, etc.) so as to obtain new elements of understanding.

More generally, the use of these tables is useful in three ways.

First, **for scenario users**, this makes it easier to access this information because it is gathered in a single section of the study report, and thus allows for more transparency, as transparency is about providing digestible intelligence. This is true both for the **understanding of a single scenario** (we can see which boxes are filled in or not, which characteristics have been subject to in-depth analysis, etc.), and for the **inter-study comparison** of these characteristics which is thus greatly facilitated.

Second, **for the scenario community**, it is a real **gain in transparency**. This makes it easier for the different stakeholders in the community to **access** the data, use it to run other models, learn from new methods, etc. It is an effective way to promote debate, to refine hypotheses, to share good practices, and more generally to reinforce and connect the community. Indeed, as described in Transparency paragraph (see Future study file), transparency is a key element to **foster trust** and therefore **build a fertile ground** for the scenario community. This is considered by researchers as one of the most efficient ways to grasp complexity.

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

Finally, **for scenario producers**, the use of these transparency tables allows to build trust, both towards users of their study, and within the scenario community. This makes it possible to better communicate their messages (see Trustworthiness paragraph in Future study file).

These tables can also provide a basis for scenario producers who wish to ask themselves new questions. For inexperienced script producers, this can be an interesting starting point for inspiration and thus promote the emergence of new future studies. For more experienced producers, it is an opportunity to ask new questions that may lead to additional elements (for example on the impact of climate change on different technologies).

Recommendations for scenario producers:

So as to participate in a common effort within scenario community, scenario producers may use the presented transparency tables. The following sections describe these tables and provide guidelines in the way they may be used.

2. The characteristics described in the tables can evolve over the study timeframe

Most of the characteristics presented in the tables can vary over time and thus during the scenario timeframe, especially due to technical progress. This evolution in technology maturity can be expressed through various characteristics, either exogenously or endogenously. For example, technical progress often appears in cost characteristics. The choice of characteristics that are evolving can be explained.

An often used method to determine a technology characteristics evolution is to apply a **learning rate** to its costs. As described in (Dii, 2012) : "a common (and technology independent) way of estimating cost reductions over long time periods is that of learning curves. This empirically proven approach shows that maturing technologies undergo a rate of cost reductions that depends, in a roughly linear fashion, on how often the installed capacity of the technology doubles. Thus, the worldwide installed capacity of a technology at the beginning of the time horizon under consideration has a major influence on the rate of cost reduction per installed GW."

Learning rates are widely used, as in model PRIMES, (ECF, 2010) or (Greenpeace, 2015). (ECF, 2010) uses for example two types of learning rates: a reduction in cost per doubling of cumulative installed capacity for new technologies, and a yearly improvement for 'established' technologies. The cost reduction is directly applied on the technology CAPEX. The values of these rates are determined through industry participation workshops.

However, as argued in (JRC, 2014), this approach is a common simplification. Cost reductions are indeed the result of more complex processes. They thus recommend to use learning rate with caution. Pursuing price reduction under certain limits could indeed not be feasible in reality. Hence a narrative could be provided to explain how and why the planned cost reduction will occur in the scenario. (ECF, 2010) for example substantiates the CAPEX reduction of some plants by providing values about the improvements of their efficiency.

Recommendations for scenario producers:

A narrative may be provided to justify the chosen characteristics evolution over time. For example, in the case of learning rates, insights about relocation and prices of imports may be discussed.

Do prices decrease due to evolutions in the production places? Do prices include possible tensions about materials/goods?

3. Table of technical characteristics for generation units

In this section, we consider the different technical characteristics of generation units. They are summed up in this table (Figure 5), and developed in the following paragraphs:

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

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

Figure 5: Generation units' technical characteristics table

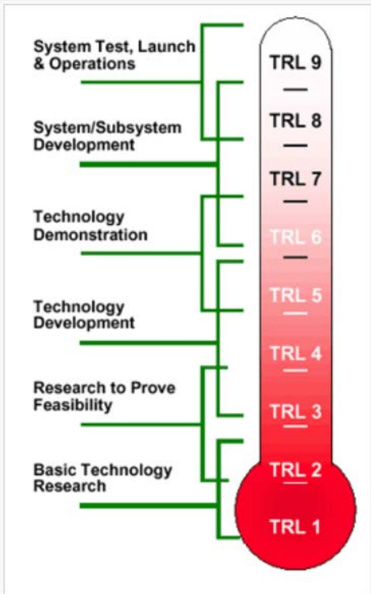
NB: To integrate technologies that modify several characteristics of plants such as CCS, several option can be used:

- describe all the modification that CCS (or other technology) brings in a specific paragraph. E.g.: plant efficiency is reduced by 20% while CO_2 emissions are reduced by 50%, etc.
- each technology using CCS can be a new row in the table (one row for coal and one row for coal+CCS, etc.)

In any case, a specific paragraph about CCS is useful to discuss considerations such as competition about storage space (as with industry), CO_2 transport network and its distance to each generation unit equiped with CCS, abatment cost of avoided ton of CO_2, etc.

d. Technology maturity : a combination of TRL and CRI indicators

The **Technology Readiness Level** scale is a rating system used to evaluate how mature a technology is. The scale starts at level one (basic technology research) up to level nine (system test, launch and operations). As explained in (IEA, 2015): « *TRLs can be used to assess how far a technology is from market, and hence the uncertainties in other evaluation metrics.* »



NASA Technology Readiness Levels

Source: Wikipedia

It can be used for generation unit as well as storage units, as in (Brouwer, van den Broek, Zappa, Turkenburg, & Faaij, 2016) for example. The TRL indicator does not take into account any notion of costs, but it can be linked with other indicators such as the discount rate: higher levels of technology readiness signal indeed lower perceived risks (Engel, Dalton, Anderson, Sivaramakrishnan, & Lansing, 2012) , and thus lower discount rates.

The TRL indicator has been designed to be used in the research and development sector, particularly for **systems not yet commercially available commercialized**. Thus, any large-scale electricity production technology in use today is rated nine (i.e. the maximum) on the TRL scale.

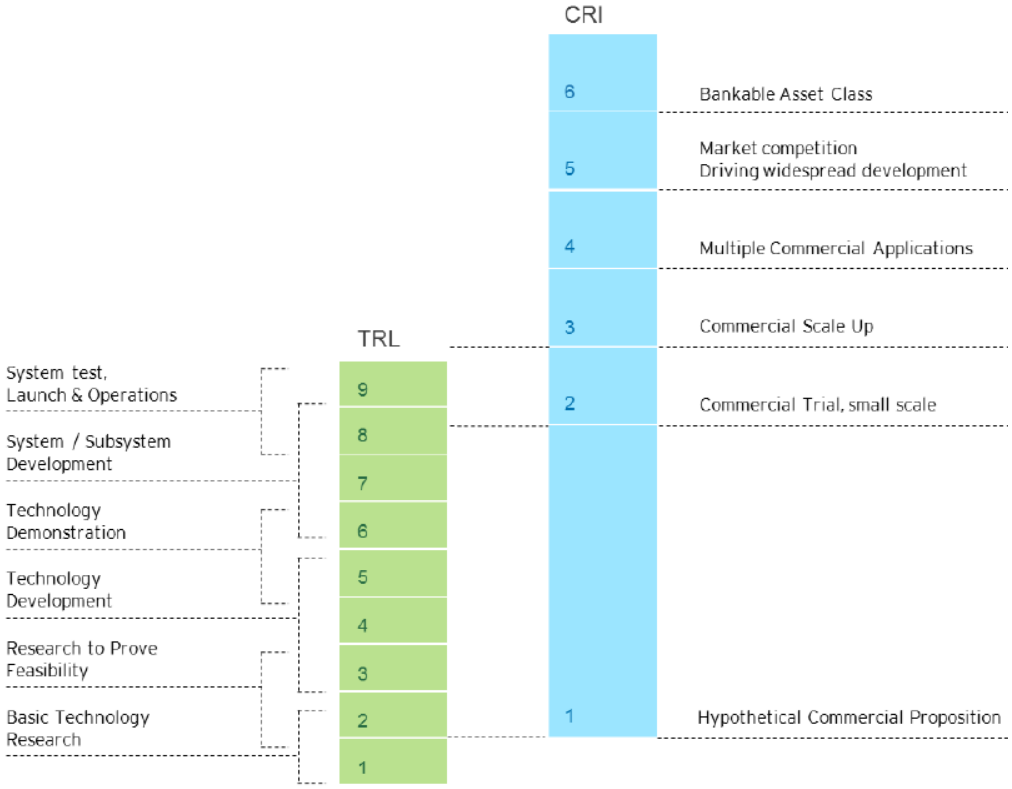
This indicator can be useful in the scenarios when trying to evaluate how mature an emerging technology is. For example, it can help to determine the year of availability of a specific technology in a scenario; and/or be used to eliminate some technologies for a particular scenario. This method has been used in the study (Association négaWatt, 2017): in order to make technologies "realistic choices" (i.e. the technologies will be available soon enough, in sufficient quantities, with reasonable costs and acceptable impacts), only those with a rated TRL above nine have been "significantly used" in the scenario.

The study (ANCRE, 2017) uses the TRL indicator as well: a recommendation of this study is to pursue and orient a significant part of the research towards projects with a 'medium' TRL (i.e., between four and seven).

TRL can be completed with other indicators. (Association négaWatt, 2017) study presents for example Manufacturing Readiness Level (MRL) and the Environmental & Social Readiness Level (ESRL). These indicators enable to address other dimensions of technology maturity. However, these two scales tend to overlap with the TRL scale (i.e., for every given technology TRL level, there is the same corresponding MRL and ESRL level most of the time). Furthermore, the MRL and ESRL scales do not go significantly « higher » than the TRL scale. In the end, it seems they do not really bring valuable further insights to select technologies.

As the TRL indicator does not allow any distinction of already-mature technologies, a more interesting complementary indicator would be the Commercial Readiness Index (CRI). It has been developed by the Australian Renewable Energy Agency (ARENA) for that specific purpose. The CRI indicator takes into account costs and is mainly directed to technologies with a high TRL value. CRI may thus be a good indicator for scenarios, especially for renewable energy technologies:

Figure 1: **TRL and CRI**



Source: (ARENA, 2014)

(IEA-RETD, 2017) explored the use of CRI for **renewable energies** as a **tool helping decision making** when implementing public policies. For example, the study explores and shows how a technology such as solar PV in Germany, with a TRL of 9 in 2003, progressively climbed the CRI scale thanks to several energy policies (see corresponding annex). This study concludes that the CRI can be useful at different levels and lists its limitations as well. These conclusions are presented in corresponding annex.

e. Unit capacity

This column can be used to **explain choices about the capacity of production, or storage units.** *For each technology, is a unitary capacity value set? Is the value changing over time during the scenario? Can different plants of the same type be built with different capacities on the same year, and if so, how is the choice made?*

Moreover, it may also be interesting to specify if the approach toward overall installed capacity is discrete or continuous. *Is it possible to install any given capacity value or does it have to be a sum of individual plant unitary capacities? Is it possible to install "one third of a power plant"?*

As the other characteristics presented here, this one it is not necessarily useful in some studies, but it can be found in others. The unit capacity can be expressed in Watts (kW, MW, GW) but also as in W/m², or W/any relevant functional unit. In this case, it may be useful to provide additional information. For example, in the case of W/m² for solar panel, it can be useful to specify these are m² of ground or m² of panel.

Some studies provide detailed analyses of how other technical characteristics may interact with unit capacity and thus anticipate its evolution over time. As an example, (ADEME, 2015) discusses new types of wind turbines with higher unit capacity with regards to characteristics such as the size of the rotor, the specific surface, etc.

f. Energy yield

The energy yield of a plant is the **ratio between input and output energy**, expressed as a percentage. This parameter is mainly used in the case of fossil fuel plants. It may evolve during a scenario, increasing most of the time as a result of technical progress. Such evolution over time may be linked with cost reductions.

(ECF, 2010) for example indicates the efficiency evolution of new plants in its scenarios between 2010 and 2050: from 58% to 60% for gas plants and from 45% to 50% for coal plants.

g. Life duration

This is a useful parameter to understand the **power generation mix evolution pace**. It may be interesting to specify this indicator: *is it a "technical" lifetime or an "economic" lifetime that is considered? Something else? What definition is used?*

For example, (ECF, 2010) defines the economic lifetime as "the average depreciation life" (e.g., 40 years for a coal-fired power plant, and 30 years for CCGT).

h. Dispatchability level

An important and often used distinction regarding the operability of a plant is whether it is **"dispatchable"** or not. This distinction may be interesting, and some studies such as (ADEME, 2015) use it, as for renewables technologies used in the scenario. Non-dispatchable units can sometimes be called **"variable"** (the term "intermittent" can also be found, but is generally deemed to be more pejorative).

(ECF, 2010) for example defines dispatchability as "the ability of a resource to respond to specific instructions to operate in a given mode at a given point in time with a high degree of reliability". Dispatchability is linked to the presence of an input energy resource which is stored, allowing to modulate the output power of a plant at the appropriate time; as opposed to technologies depending on an energy flow that cannot be stored as such for their production.

Scenario producers could also chose to bring **additional information about the dispatchable/variable nature** of generation units. Indeed, it may happen that some 'variable' technologies can be controlled to a certain extent, typically downwards. Also, some technologies usually described as dispatchable may be subject to unexpected constraints, and therefore, in some ways, may show downward variability. Therefore, this type of distinction could be introduced: dispatchable upwards and/or downwards; variable upwards and/or downwards.

In any case, since there is not exact consensus on these definitions, the best option is that the scenario producer provides its own definition.

Moreover, it may also be possible to specify the **"level of dispatchability"**, and by doing so to avoid choosing between dispatchable or variable. To that extent, a set of specific characteristics can be provided, such as ramp up and ramp down capabilities, minimal or maximal operating points, etc. (see Flexibility paragraphs in Power system operation file for more insights on this topic).

i. Dispatchability main constraints

To complete information about the level of dispatchability of a generation unit, it can be useful to provide information on its main dispatchability constraints to understand under which limits a dispatchable unit is still dispatchable.

One can therefore list:

- **Constraints on the energy stock and/or energy flow**. For example: the dispatchability of hydropower plants remains limited by the level of precipitation and/or the capacity of the reservoir; failures in coal storage silos have in some cases prevented coal power plants from operating properly; the dispatchability of gas power plants in peak conditions can be limited by the maximum flow of the gas network that supplies them, etc.
- **Economic constraints**. One example is the costs to stop and start a plant, which explain why some power producers prefer to pay for electricity production during negative electricity price periods rather than temporarily shutting down the plant.
- **Regulatory constraints**.
- Other constraints related to **plants specificities** can lead to limited electricity production, such as the heat production part for CHP plants, cooling requirements for nuclear power plants, etc.

j. Resource predicatability

Another important element with regard to dispatchability is the **ability to predict plant production**. This depends on how the resource is stable in a day and over the year, and also on the evolution of knowledge and modelling capabilities on this particular resource.

It may also be interesting to provide considerations about the ability to predict any constraints on energy stock or flow.

k. Resource potential

For each type of technology, it is possible to define a maximum resource potential. However, it is important to specify what **the type of potential** is.

On the one hand, **five types of potential can be listed for renewable resources**. They can be expressed either in energy units per year (TWh/year for example) or in power (GW for example). (Greenpeace, 2012) summarizes what the five types of potential are as represented in the box on the right.

Theoretical potential may evolve for some resources if new discoveries are made (e. g. new terrain suitable for hydropower), and according to changes in the environment that provides the renewable resource (e. g. forest degradation, which can no longer produce as much wood each year). However this is not the case for solar irradiation for example. Conversion potential evolves with technical progress, while economic potential evolves according to the costs of exploiting the resource, and according to the price on the markets.

On the other hand, **for non-renewable resources, a distinction is made between reserve and resource**. The resource is the total existing quantity of a given material, while the reserve is the known, technically and economically exploitable quantity of this material. The resource therefore corresponds in a way to the theoretical potential, while the reserve corresponds to the economic potential.

box 8.1: **definition of types of energy resource potential**[77]

Theoretical potential The physical upper limit of the energy available from a certain source. For solar energy, for example, this would be the total solar radiation falling on a particular surface.

Conversion potential This is derived from the annual efficiency of the respective conversion technology. It is therefore not a strictly defined value, since the efficiency of a particular technology depends on technological progress.

Technical potential This takes into account additional restrictions regarding the area that is realistically available for energy generation. Technological, structural and ecological restrictions, as well as legislative requirements, are accounted for.

Economic potential The proportion of the technical potential that can be utilised economically. For biomass, for example, those quantities are included that can be exploited economically in competition with other products and land uses.

Sustainable potential This limits the potential of an energy source based on evaluation of ecological and socio-economic factors.

Source : (Greenpeace, 2012)

Several more or less detailed methods exist to define all these resource potentials, both for renewables and non-renewable sources. It can be a narrative, as in (ECF, 2010) on fossil energy reserves, or a detailed approach for each sector as in (ADEME, 2015)[7], where the potential for each renewable sector is studied with a high geographical granularity and topological and societal constraints. Legislative and economic aspects are also taken into account using several databases.

As there can be a competition between different resources, scenario producers should provide information on the global consistency of their resource assessments. Such a global approach requires to solve extraction conflicts between several resources (such as land use conflicts).

l. Maximal installation rate

In the real world, there are obviously different types of **limits** to the installation pace of different units. However, it is impossible to decide on a single maximum rate value: those limits depend on the hypothesis made in the storyline and therefore vary from one scenario to another. If no maximum installation rate is calculated, then it can be interesting to qualitatively substantiate the observed installation paces in the scenario.

This can be linked to resource potential, as resource quality can decrease when new installations progressively appear at the best locations. Maximum installation rate also depends on the **amount of skilled workforce** in each sector required to meet the human resource requirements in time (see employment data column in Economic characteristics table).

m. Production profile

Production profile is the **hourly production potential** of a generation unit. For a renewable variable units, it depends directly on the resource at the location where the unit is installed: the PV production profile depends on irradiation profile, wind power profile depends on the wind profile, etc. Therefore, production profile varies depending on the location, the day, etc. This enable to introduce the previously mentioned decrease in renewable resource quality as best locations are progressively used.

Production profiles are mainly useful for variable renewable installations. For other types of installations, it is possible to use the "base load / mid-merit / peak load" categorization. It tends to be less and less used as the share of variable renewables increases in the electricity mix, but it can still provide useful information. (ECF, 2010) for example distinguishes "baseload plants" that "operate generally around the clock, at least at part load" and "mid-merit plants" that "are turning up and down, and even on and off, with normal daily fluctuations in demand". They categorize coal-fired power plant as "baseload plants" and gas-fired power plant as "mid-merit plants". This categorization depends on the choices made on the study. In the real world, it changes from one country to another.

n. Load factor

This parameter can be expressed as % or h/year.

For **variable generation technologies**, the load factor is a partly exogenous data. It can be used to calculate the resource conversion potential as load factor value directly depends on the renewable resource. It may also vary during the scenario due to technological progress.

For **dispatchable generation technologies**, the load factor is rather an endogenous variable according to the choices made in the scenario storyline and/or results of the model simulation. It can be linked with choices about the previously presented base load / mid-merit / peak load categorization.

o. Availability factor

Load factor can be linked to availability factor, which indicate what **proportion of the time a given plant may actually be in use** for electricity production. This enable to introduce plant closure planning, and therefore plant

[7] This detailed approach is transparently explained in the study and provides useful methods and information on renewable resource potential.

unavailability due to unforeseen events, maintenance operations, etc. It may be interesting to specify both the average value of this availability factor and its value when the plant is in a peak situation.

p. System storage function

Some generation technologies may have an **additional storage function** besides their production function. This additional function can be either 'system' or 'local' storage:

- A ***system storage function*** allows to store electricity from other production units. This is the case for the great majority of storage systems, which thus enable to provide a storage function 'from the power system point of view'.
- A ***local storage function*** only permits energy storage for the given specific technology. This is the case, for example, for concentrated solar power technology which stores energy under heat form. This type of storage function does not provide any storage capacity for the system as a whole. However, it enables the technology to improve its dispatchability.

Therefore, it is not relevant to specify local storage function here (it can instead be mentioned in columns related to dispatchability). Only system storage function should be specified in this column, and a corresponding row in the storage units technical characteristics table should be added.

NB: In the case of hydropower, it may be interesting to distinguish hydropower alone (no system storage function) from mix pumped hydro storage (PHS) (both system production and storage function) and from pure pumped hydro storage (storage function only). Indeed, resource constraints are different for mix PHS and pure PHS.

q. Ancillary services

Some production units also provide **other types of services from a system perspective**. These are called ancillary services, such as voltage control, rotor angle stability, flexibility function, reserve function, inertia function, etc. Detailed and illustrated explanations about ancillary services can be found in Power system operation file.

r. Impacts from climate change

Climate change we are experiencing has and will have increasing impacts which can affect generation infrastructure in various forms. It may be interesting to develop these elements for each technology, and to specify for example if **adaptation measures** are implemented to reduce exposure to **physical risks**.

E.g.: the increase in frequency and intensity of extreme events as well as the rise in sea level can damage some equipment such as onshore and offshore wind turbines, disturbance of water cycle can impact water resources and therefore hydroelectric potential, increasing temperatures and heat waves can reduce PV panel energy yield and affect cooling capacity for nuclear power plants, etc.

Some effects can already be observed today, such as the decrease in snow stock and therefore of hydroelectric potential. For the other effects that could be negligible in the medium term, several opinions consider that many impacts will no longer be negligible as early as 2040-2050. Therefore, it might be interesting to estimate costs of adapting to these impacts (see Power system inventory in Economic Evaluation file).

NB: There seems to be a lack of information on this subject. Climate models are indeed not able to provide accurate estimates for the 2040-2050 horizon since they are rather designed to assess impact in year 2100.

4. Table of technical characteristics for storage units

Along with the construction of models and scenarios, storage issue is **one of the most studied** in the field of renewable energies integration into electricity networks (Hache & Palle, 2018). Storage units, if deployed on a large scale, indeed make it possible to store electricity when it is in surplus and to restore it when it is needed at the power system level, which is a highly useful service when the power system includes a high share of variable energy sources. Electricity storage is achieved by **transforming electricity into another form of storable energy** and then by transforming it back when needed. There are many possible techniques for that purpose, through three main forms of energy: mechanical, chemical, and thermal.

Here is a list of main electrical storage systems: pumped hydro storage (PHS), thermal energy storage (TES), compressed air energy storage (CAES), small-scale compressed air energy storage (SSCAES), energy storage coupled with natural gas storage (NGS), energy storage using flow batteries (FBES), fuel cells—Hydrogen energy storage (FC–HES), chemical storage, flywheel energy storage (FES), superconducting magnetic energy storage (SMES), energy storage in supercapacitors. (Ibrahim, Ilinca, & Perron, 2008)

The presented **table of technical characteristics for storage units** is composed of the following columns.

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

Figure 6: Storage units' technical characteristics table

TRL

The Technology Readiness Level indicator applies to both production and storage units. (see paragraph on TRL)

Type of application

In order to understand what type of service the storage unit provides, it may be useful to specify whether it is a large unit at the production level or a small unit at the consumer level that provides a demand flexibility service. It may also be interesting to specify whether the considered unit is stationary or mobile.

Storage duration

This is the main temporal aspect of storage units. Each type of storage system can store energy either on the short-term or on the long-term. For example, several types of periods can be distinguished: intraday, daily (or intra-week), seasonal, etc.

Storage capacity

This is the quantity of available energy in the storage system after charging. This is obviously a key characteristic of storage systems. This information can be completed with mass and volume densities of energy: these represent the maximum amounts of energy accumulated per unit of mass or volume of the storage unit, and demonstrate the importance of mass and volume for certain applications. (Ibrahim et al., 2008)

Power output

This is the speed at which stored energy can be released and thus determines the time needed to extract it. This is another key characteristic depending on the maximum power needed, especially during peak hours.

Cycling capacity

This refers to the number of times the storage unit can release the energy level it was designed for after each recharge, expressed as the maximum number of cycles (one cycle corresponds to one charge and one discharge). This is the main durability indicator for storage system. All storage systems are subject to fatigue or wear by usage. This is usually the principal cause of aging, ahead of thermal degradation (Ibrahim et al., 2008). Therefore life duration is not a relevant indicator to express storage system durability.

Efficiency

This is the ratio between released energy and stored energy. It enable to estimate how much energy is lost when it requires to be stored.

Storage potential

As with for the resource potential deposit for production units, it may be interesting to estimate the storage potential, quantitatively or qualitatively, as well as the main limits that can be identified. (ECF, 2010) for example states that "European hydro plants have unused potential for optimization of their storage potential". The study uses this identified margin in its scenarios and also specifies that « As these systems require mountainous areas this type of storage has some geographical limitations and therefore cannot always be placed at locations where it might be needed most. Innovative concepts on artificial islands in the sea have been launched".

For other types of storage such as batteries, one can also think about limits related metals criticality (see section on environmental assessment).

Operational constraints

Constraints in the storage systems operation mainly come from safety issues (explosions, waste, bursting of a flywheel, etc.) and operational conditions (temperature, pressure, etc.) Considerations about monitoring and control equipment may be added as this equipment can have consequences on both the quality and safety of storage.

Impact from climate change

As for generation technologies, storage technologies are exposed to physical risks due to climate change and adaptation measures can be required.

E.g.: the increase in frequency and intensity of extreme events as well as the rise in sea level can damage some equipment, increased temperatures and heat waves can reduce efficiency and accelerate the degradation of batteries, etc.

Finally, **other more specific characteristics** can be added if the scenario producer considers it useful. It may include insights about self-discharge (which is the portion of the energy that was initially stored and which has dissipated over a given amount of non-use time) or other characteristics that sometimes depend on specific installation parameters such as autonomy or discharge time.

5. Table of economic characteristics

Concerning economic characteristics, other files already address in depth several aspects: see files one economic evaluation, job transition, LCOE and discount rate.

Here are the main characteristics that can be summed up in a table:

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

Figure 7: Economic characteristics table

CRI

CRI indicates the commercial readiness level of a technology and can be a good complementary parameter to the TRL, as described in TRL paragraph.

CAPEX

Capital Expenditure of a technology are all the investments to build the unit, extend its life duration, and spare money (provision) for future expenses as dismantling or waste management. It can include the financing costs of those investments (i.e. capital costs). CAPEX can be expressed as a euros per unit of capacity (e.g., €/kW).

OPEX

Operating Expenditure of a technology comprises all costs required to make the unit run correctly. It includes fixed costs as worker wages and regular maintenance operations and variable costs such as the purchase of fuel and quotas on carbon market for some generation technologies. A narrative about fuel prices evolution can be provided.

Both for CAPEX and OPEX, what is included may be clearly defined by scenario producers since the same terms can sometimes have different meanings depending on the study (e.g., "variables costs"). See Economic Evaluation for more details on CAPEX and OPEX.

i-LCOE / i-LCOS

As described in the note about LCOE, i-LCOE indicator (for "investors LCOE", as opposed to "system LCOE"), indicates the cost of electricity produced for a given technology, for a given year. A similar indicator exists for electricity storage system: the i-LCOS (investors Levelized Cost of Storage) and indicates the cost of stored (and then released) electricity. Some scenarios use this indicators to determine the supply-side mix while other do not. See LCOE file for a detailed analysis of LCOE indicator.

WACC

Weighted Average Cost of Capital is the discount rate allowing to integrate the remuneration expected by financers (i.e., capital costs) in calculations for a specific project. The WACC value can have a significant impact on the profitability of a project, especially for capital-intensive investments (i.e. projects with high CAPEX and low OPEX) like most of decarbonized generation technologies. A justification of the chosen value and its evolution according to the several types of risks taken into account (country risk, delivery and legal risks, etc.) can be provided. See private discount rate paragraph and its explanation box on WACC in Discount rate file for more details.

Employment data

In this column, scenario producers can include information such as employment factors and considerations about the amount of skilled workforce in the given sector. Indeed, meeting the human resource requirements of sectors in rapid expansion requires education and training policies to avoid bottlenecks. See Job transition file for more details.

6. Table of environmental characteristics

Every type of unit interacts with its surrounding environment, in two ways: by extracting resources from it and/or by releasing substances in it. By and large, this participates to several issues that can be either local or global.

Some of these interactions can be easily measured and expressed as physical quantities, while others are more of a diffuse nature and are better expressed qualitatively. For quantitative impact, many data sources present value of resource extracted or substance released by unit of produced (or stored) energy: gCO2eq/kWh, gSO2eq/kWh, etc. (United States Department of Energy, 2015) study provides to that extent tables on GHG emissions, air pollutants, water use, land use and material criticality for different technologies (see corresponding annex).

Here is the environmental characteristics table :

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

Figure 8: Environmental characteristics table

All the following elements are explored more in detail in Environment section. For each element, scenario producers can present qualitative consideration in any case and quantitative values (see corresponding annex).

Material criticality

Metals and other materials are, along with fossil fuels, one of the main stock resources that we use on a large scale on the planet. With increasing exploitation on a global scale, the depletion of several specific metals and materials raises geological criticality questions, as for copper for example.

Land use

Some infrastructure require larger areas than others, which can raise competition issues about land use such as food production.

Water use and pollution

The impact on water is both due to withdrawals and substance releases into watercourses such as hotter water, in the case of thermal power plants, or indirect acidification of watercourses due to substances first emitted into the air. Water withdrawals as with hydroelectricity or the need for cooling water from thermal power plants can cause competition on water resources.

Climate change

Climate change is due to greenhouse gases (GHG) emissions, and especially CO_2 in the case of power system infrastructures. Concerning CO_2 emissions, two main categories can be distinguished :

- High-carbon technologies are those using fossil fuels combustion and have significant emissions occuring during use phases due to combustion in addition of the smaller emission during production/end-of-life phase due to construction work. These generation technologies are, from the most emissive to the least emissive, Coal – Oil – Gas.
- Low-carbon technologies are all the production technologies. Significant emission only occur during production/end-of-life phases due to construction work. Solar PV has the highest value among those technologies. Wind, geothermal and nuclear usually have the lowest values.

Air pollution

It is the main direct cause of death due to the use of electrical system infrastructure. It is mainly due to several substance emitted during combustion such as *particulate matter, sulfur dioxide, nitrogen oxides, carbon monoxide, etc.* Exposure to these pollutants can damage people's cardiovascular, respiratory and nervous systems, increasing the risks of lung cancer, stroke, heart disease, chronic respiratory diseases and lethal respiratory infections. As for GHG emission, coal has the worst impact by unit of produced energy. Unlike GHG emissions, this is not a global issue but rather a local one.

Solid waste

Different types of solid waste, including nuclear waste, can be generated when using power system infrastructures.

Biosphere

More difficult to measure than other characteristics, the impact on the biosphere can be assessed qualitatively. One can think of reservoirs dam construction implying ecosystem damage, aquatic ecosystems perturbation during use phase, and other types of problems if dam breaks; or impacts of floating offshore wind turbine that can be both positive and negative as is marginally kills some species but also encourages biodiversity development by protecting areas; etc.

NB: other categories can be defined. The impacts related to the release of substances can typically be presented in two ways: either by major type of end-point impact (climate change, human health, etc.) or by type of substance emitted. Indeed, the same substance can participate in several end-point impacts, and each end-point impact can be the consequence of the emissions of several substances (see LCA approach).

For example, CO_2 contributes to greenhouse effect and therefore to climate change, but also to acidification of the oceans. Similarly, SO_2 contributes to air pollution, but also to the acidification of water, soil, etc.

7. Table of social characteristics

Finally, in terms of social aspects, only a few columns are presented because most of these aspects are more **related to systems as a whole** than to particular technologies. Three columns are distinguished here, in line with the distinction made in Desirability section:

	Landscape	Safety risks	Other human ecology impacts
Hydro			
Gas			
Batteries			
...			

Figure 9: Social characteristics table

Landscape impact

Some infrastructures modify local landscapes such as overhead lines, wind turbines, etc. It can be a key factor in local acceptance problems. This is linked to the concept of place attachment.

Safety risks

One can think of risk of fire starting, risk of leakage (such as CO_2 leakage in the case of CCS), explosion risk (as for biogas plants if not properly supervised), nuclear accidents risks, risk of flood (when a dam breaks for example), the risks related to working conditions for workers in this sector, etc.

Other human ecology impacts

This related to impacts such as wind turbines generating noise or shadows, or smells from biogas infrastructure may generate smells, possible population displacements but also possible recreational areas or irrigation support when a dam is installed, etc.

8. How to use the tables: indicative instructions

First, the scenario producers lists the technologies with the desired **level of granularity** (one or two types of wind power or solar PV, two or three types of hydropower, etc.), with justifications for these distinctions and possible explanations for why certain technologies are not taken into account (e.g., for of robustness reasons).

Then, the tables are intended to be flexible: each scenario producer decides both which boxes will be filled in and what should be included in it (a value, a qualitative estimate, a reference to a paragraph of the report, etc.) Each of the five tables can be presented either once for the entire study, or for each scenario (for example according to the number of characteristics that are modified between the scenarios).

We suggest to fill in the table as follows:

- First for the **rows**, enter all the technologies used for the construction of the scenario mix. A justification for this choice of possible technologies is welcomed. *Why this list of technologies? Have any technologies been deliberately exclued? Is a TRL or CRI criterion used?*

- Then for the **columns**, ignore those that do not concern any of the technologies in the scenario. This means these characteristics are not useful in the study to determine the supply-side mix. These columns can be grayed out, or filled with an indication such as "not used". Each column can be subdivided for greater granularity of information if needed. Similarly, columns can be added if characteristics useful in the study do not appear in these templates.

- Finally, for the **all other boxes**, each can be seen as one paragraph in which the characteristic can be filled in and explained. In each case, since these data are normally already processed in the scenario, it is possible to simply refer to the corresponding paragraph in the report. Here is a list of useful items of information that can be introduced:

- **Is this value unused or confidential?** In this case, it is useful to indicate it with a mention *(like "not used" or "confidential").*

- **Otherwise, what is the given value?** It can be quantitative or qualitative.

- **How is it determined?** If it is exogenous, the source can be presented (workshop, literature, discussion with industry stakeholders, academics, other expert opinions, etc.). If endogenous, the calculation mode is relevant. Indeed, each variable can be a hypothesis or an outcome, depending on the scenarios. It is up to the scenario producer to choose how to introduce them. Also, some characteristics can sometimes be used for storytelling purposes only (i.e., they are not used when determining the supply-side mix). This can also be interesting information. In addition, the units used may be specified as it can change from one technology to another. Also, if the variable is an aggregate (e.g., "OPEX"), what is contained may be explained.

- **Does the variable change during the scenario?**

- **Which explanatory elements?** What substantiates the consistence of the value and its evolution? Narrative elements can be provided. E.g., for an unspecified value: « this variable is redundant with others » (as other combined quantities already enable to get the same information), or « this quantity is outside the scope of the study driving question and is therefore not useful », etc.

NB: every study already disclose this type of information for some given characteristics. The idea here is to generalize this type of practice and to centralize information in a single place.

Here is a short example for a fictional study:

	TRL	Unitary capacity	Efficiency of new plants	Life duration (years)	Load factor	...
PV		See paragraph 2.1		25		
Wind		See paragraph 2.2		30 Repowering has been considered (see p44)		
Hydro	Not used	See paragraph 2.3	Not used. See p105	50	Confidential data	
Nuclear		See paragraph 2.4		40 See paragraph 3.4 for more details		
Coal		See paragraph 2.5		40		
Gas		See paragraph 2.6				

Figure 10: In this fictional study, six power generation technologies are considered. The first characteristic, the TRL, is never used. The unit capacity is described in respective paragraphs for each technology. The plants energy yield is not a used but some consideration on it are provided in one part of the report, possibly to explain why it is not a useful characteristic here. Life durations are specified, with additional details for wind and nuclear power. Load factors are used but the information is confidential. Finally, the study goes into an in-depth analysis of gas-fired power plants, and dedicates a paragraph to it that explores considerations about on several characteristics and the links between them.

C. The grid

1. In ETS, transmission grid reinforcement is sometimes studied, distribution grid evolution is never studied

The transmission grid is rarely finely modeled. Some studies models it as a fictional single node (copperplate model), as if all plants and consumers were connected all together at a single point (ADEME, 2012; Association négaWatt, 2014). The hourly load-supply balance can be checked with these simplified models if load is properly modeled (taking into account the spatial variability of load, for example as a function of different temperatures, winds and weather conditions) as well as supply (which also has a spatial variability, all the more important with larger shares of VRES).

When transmission grid needs to be modified because of significant changes in load and/or supply levels and/or location, models with the adequate spatial resolution are required (IRENA, 2017). Basic transmission grid models depicts it as links between individual nodes representing countries, or regions interconnected with each other. For example, (ADEME, 2015) models the transition network as links between regions representing the inter-region electricity flows, providing information on the necessary reinforcements of transmission between regions. Scenarios using PRIMES model (such as (ECF, 2010; European Commission, 2011; European Commission, 2016; SFEN, 2018)) model the transmission grid through links between countries, which are themselves represented as single nodes (E3MLab, 2017). This model can provide information about interconnection strengthening needs, but no information about grid requirements within each country.

A few models finely model the transmission grid (RTE, 2017) in order to get precise information about where and how the grid should evolve.

Distribution networks are not modelled in national, supra-national or world long-term models.

Recommendations to scenario producers

For scenarios requiring significant changes in the transmission or distribution grids (e.g. a shift to a decentralized network, or significant changes in the production locations), the various impacts should be estimated using a tool which represents finely enough the grid and its evolutions.

If the architecture of the network evolves, each transition state should be represented in order to assess the PS performances over the scenario timeframe, making sure that no transition state of the PS lead to power supply collapse.

2. Interconnections

Interconnections are the links between different, relatively autonomous, power systems. These new links imply a certain level of coupling between both PS.

Interconnections are characterized by their power transmission capacity, their voltage level and their current form (Alternative current or Direct current).

They are composed of two substations transforming the current into the proper form and at the proper voltage, and high voltage lines in between. For High Voltage Direct Current (HVDC) lines, the main cost component is the substations; hence HVDC lines are economically interesting for long distances (International Energy Agency, 2016).

Three different installation methods exist: overhead lines, underground lines and subsea lines. Overhead lines cost significantly less than underground lines, but they encounter more acceptance issues than underground lines.

Depending on these characteristics, the services provided, and the technology risks are different.

- **AC interconnections** lead to a complete coupling between both PSs. Hence a common frequency control and joint protection systems must be implemented. These interconnections require solidarity between interconnected PSs.
- On the contrary, **DC interconnections** propose more independence between the interconnected PSs: connected PSs can have different frequencies and voltages (International Energy Agency, 2016). However, compared to AC interconnections, they generate harmonics and reactive power must be generated at converter stations (see PS operation section) (Felix Wu, 2001).

Recommendations to scenario producers

Transparency on the type of interconnection which are implemented in the scenario should be achieve. The following aspects should be considered:

- Type of power transmission (AC or DC)
- Type of line which is used (overhead, underground, subsea)

More considerations on interconnections can be found in the Boundary Conditions section.

Annexes

A. Examples (among others) of how some future studies use transparency tables

These are just a few of numerous examples that can be found in future studies. We present them here to provide concrete illustrations of the use of transparency tables:

- (Greenpeace, 2015) provides detailed information on their hypotheses about the cost evolution of renewable electricity technologies, including the corresponding data sources:

"Assumptions on future costs for renewable electricity technologies in the Energy [R]evolution scenario of 2012 were derived from a review of learning curve studies, for example by Lena Neij,[21] from the analysis of technology foresight and road mapping studies, including the European Commission funded NEEDS project (New Energy Externalities Developments for Sustainability)[22] or the IEA Energy Technology Perspectives 2008, projections by the European Renewable Energy Council published in April 2010 ("Re- Thinking 2050") and discussions with experts from different sectors of the renewable energy industry. for the new Energy [R]evolution, cost decreases due to recent market developments are taken into account, leading to changes in own cost assumptions above all for photovoltaics and solar thermal power plants (including heat storages). However, for the reason of consistency, region-specific cost assumptions from WEO 2014 are adopted for biomass power plants, hydro, wind power and ocean energy. The following tables exemplarily show data used for the region OECD Europe."

This is one of the many tables provided :

TABLE 5.13 | OVERVIEW OF EXPECTED INVESTMENT AND OPERATION & MAINTENANCE COSTS PATHWAYS FOR HEATING TECHNOLOGIES IN EUROPE

	UNIT	2012	2020	2030	2040	2050
GEOTHERMAL DISTRICT HEATING*	$/kW	2,650	2,520	2,250	2,000	1,760
HEAT PUMPS	$/kW	1,990	1,930	1,810	1,710	1,600
LOW TECH SOLAR COLLECTORS	$/kW	140	140	140	140	140
SMALL SOLAR COLLECTOR SYSTEMS	$/kW	1,170	1,120	1,010	890	750
LARGE SOLAR COLLECTOR SYSTEMS	$/kW	950	910	810	720	610
SOLAR DISTRICT HEATING*	$/kW	1,080	1,030	920	820	690
LOW TECH BIOMASS STOVES	$/kW	130	130	130	130	130
BIOMASS HEATING SYSTEMS	$/kW	930	900	850	800	750
BIOMASS DISTRICT HEATING*	$/kW	660	640	600	570	530

* Without network

- (Lappeenranta University of Technology / Energy Watch Group, 2017) provides its own transparency tables, for generation units, storage units, and transmission lines:

  - Generation units table (only a part of it)

Table 2.2: *Technical and financial assumptions of energy system technologies used in the energy transition from 2015 to 2050. Assumptions are taken from Pleßmann et al. (48) and European Commission (49) and further references are individually mentioned. All technical and financial assumptions are given in currency values of the year 2015.*

Technologies		Units	2015	2020	2025	2030	2035	2040	2045	2050	REF
PV rooftop – residential	Capex	€/kW,el	1360	1169	966	826	725	650	589	537	50
	Opex fix	€/(kW,el a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	€/(kWh,el)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV rooftop - commercial	Capex	€/kW,el	1360	907	737	623	542	484	437	397	50
	Opex fix	€/(kW,el a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	€/(kWh,el)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV rooftop - industrial	Capex	€/kW,el	1360	682	548	459	397	353	318	289	50
	Opex fix	€/(kW,el a)	20	17,6	15,7	14,2	12,8	11,7	10.7	9.8	
	Opex var	€/(kWh,el)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV optimally tilted	Capex	€/kW,el	1000	580	466	390	337	300	270	246	50
	Opex fix	€/(kW,el a)	15	13.2	11.8	10.6	9.6	8.8	8.0	7.4	
	Opex var	€/(kWh,el)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV single-axis tracking	Capex	€/kW,el	1150	638	513	429	371	330	297	271	50,106
	Opex fix	€/(kW,el a)	17.3	15.0	13.0	12.0	11.0	10.0	9.0	8.0	
	Opex var	€/(kWh,el)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
Wind onshore	Capex	€/kW,el	1250	1150	1060	1000	965	940	915	900	107
	Opex fix	€/(kW,el a)	25	23	21	20	19	19	18	18	
	Opex var	€/(kWh,el)	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	25	25	25	25	
CSP (solar field, parabolic trough)	Capex	€/kW,th	547.8	427.8	369.2	326.9	304	283.6	265.4	249.5	54,55
	Opex fix	€/(kW,th a)	12.6	9.8	8.5	7.5	7	6.5	6.1	5.7	
	Opex var	€/(kWh,th)	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	30	30	30	30	
Geothermal power	Capex	€/kW,el	5250	4970	4720	4470	4245	4020	3815	3610	56,49
	Opex fix	€/(kW,el a)	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	
	Opex var	€/(kWh,el)	0	0	0	0	0	0	0	0	
	Lifetime	years	40	40	40	40	40	40	40	40	
Water electrolysis	Capex	€/kW,H2	800	685	500	363	325	296	267	248	57,58
	Opex fix	€/(kW,H2 a)	32	27	20	12.7	11.4	10.4	9.4	8.7	
	Opex var	€/(kWh,H2)	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	
	Lifetime	years	30	30	30	30	30	30	30	30	
Methanation	Capex	€/kW,CH4	492	421	310	278	247	226	204	190	57,58
	Opex fix	€/(kW,CH4 a)	19.7	16.8	12.4	11.1	9.9	9.0	8.2	7.6	
	Opex var	€/(kWh,CH4)	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	
	Lifetime	years	30	30	30	30	30	30	30	30	

- Storage units table

Table 2.3: *Energy to power ratio and self-discharge rates of storage technologies. Efficiency values are given for 2015.*

Technology	Efficiency [%]	Energy/Power Ratio [h]	Self-Discharge [%/h]	References
Battery	90	6	0	[62, 108]
PHS	85	8	0	[49]
A-CAES	54	100	0.1	[49]
TES	90	8	0.2	[48]
Gas storage	100	80*24	0	[48]

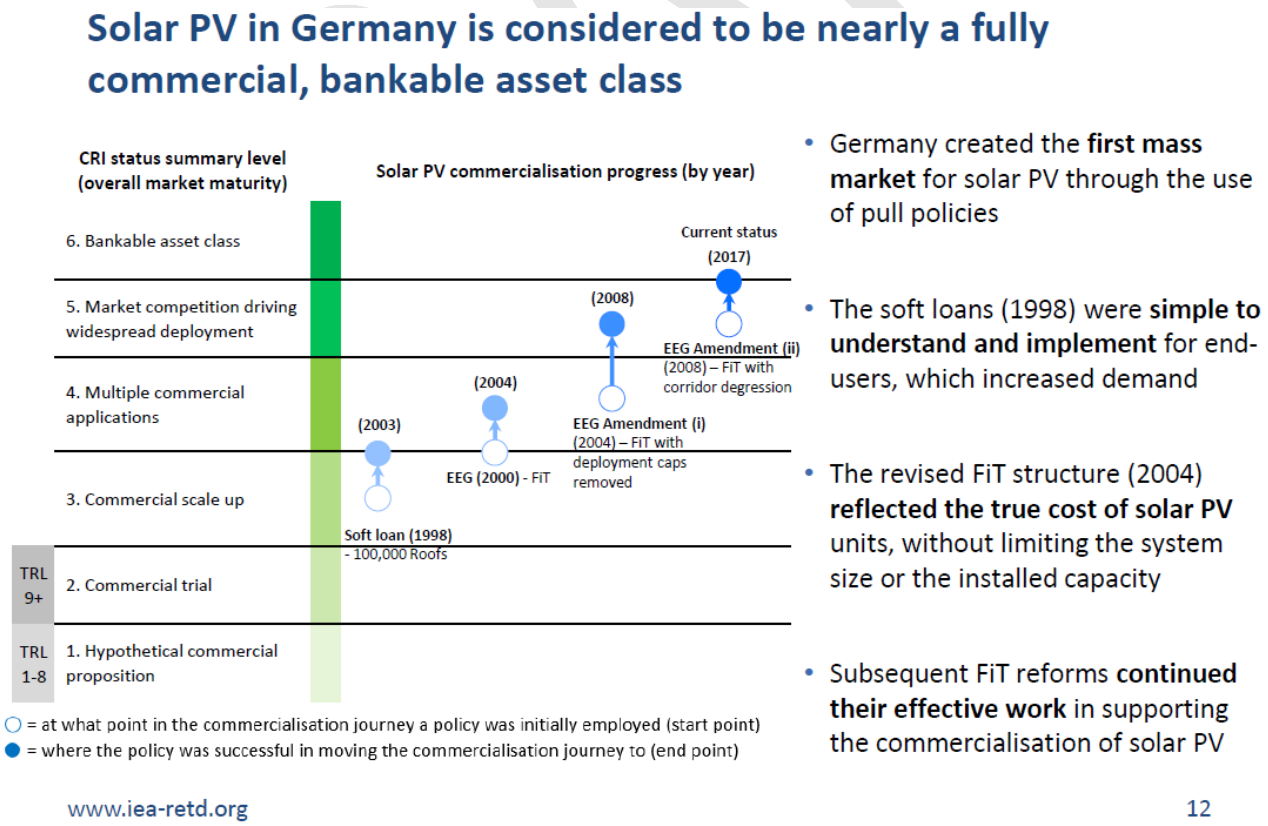
- Transmission lines table

Table 2.5: *Efficiency assumptions for HVDC and HVAC transmission for all years 112.*

Component	Power losses
HVDC line	1.6 % / 1000 km
HVDC converter pair	1.4%
HVAC line	9.4 % / 1000 km

B. Further information about Commercial Readiness Index (CRI)

(IEA-RETD, 2017) provides a table showing the CRI evolution of solar PV in Germany:



Here is a table summarizing some of (IEA-RETD, 2017) main conclusions:

Our case studies show the value of the CRI as a tool for communicating the importance of market conditions beyond technical performance for RETs

Advantages	Limitations
• The CRI helps to **prompt policy makers** to consider a range of **factors** that influence the commercial and market readiness of RETs	• The CRI does not explain **how** and **why** policies are effective
• The CRI can help to **identify the main barriers** that need to be addressed in order to help RETs to be developed and widely deployed	• It only provides a **historical snapshot** of the overall commercial maturity at one point in time
• **It can be used to Illustrate historically** which policies have affected the performance of certain indicators	• It **does not indicate** to policy makers **what are the potential interventions** that could be used to support the RETs
	• It is **difficult to translate policy lessons** from one context to another
	• The CRI assessment is **subjective** since it is based on qualitative criteria

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C. Environmental characteristics tables from (United States Department of Energy, 2015)

(United States Department of Energy, 2015) is the 2015 Quadrennial Technology Review (QTR) from U.S. Department of Energy. It examines the status of the science and energy technology with a focus on technologies with commercialization potential in the midterm and beyond. In the chapter 10 of the study – "Concepts in Integrated Analysis" – five tables about the following environmental characteristics are presented: material requirements, land use, water use, GHG emissions and air pollutants emissions. This can be a good example of data that could be used in the table of environmental characteristics.

Table 10.4 Range of materials requirements (fuel excluded) for various electricity generation technologies[52]

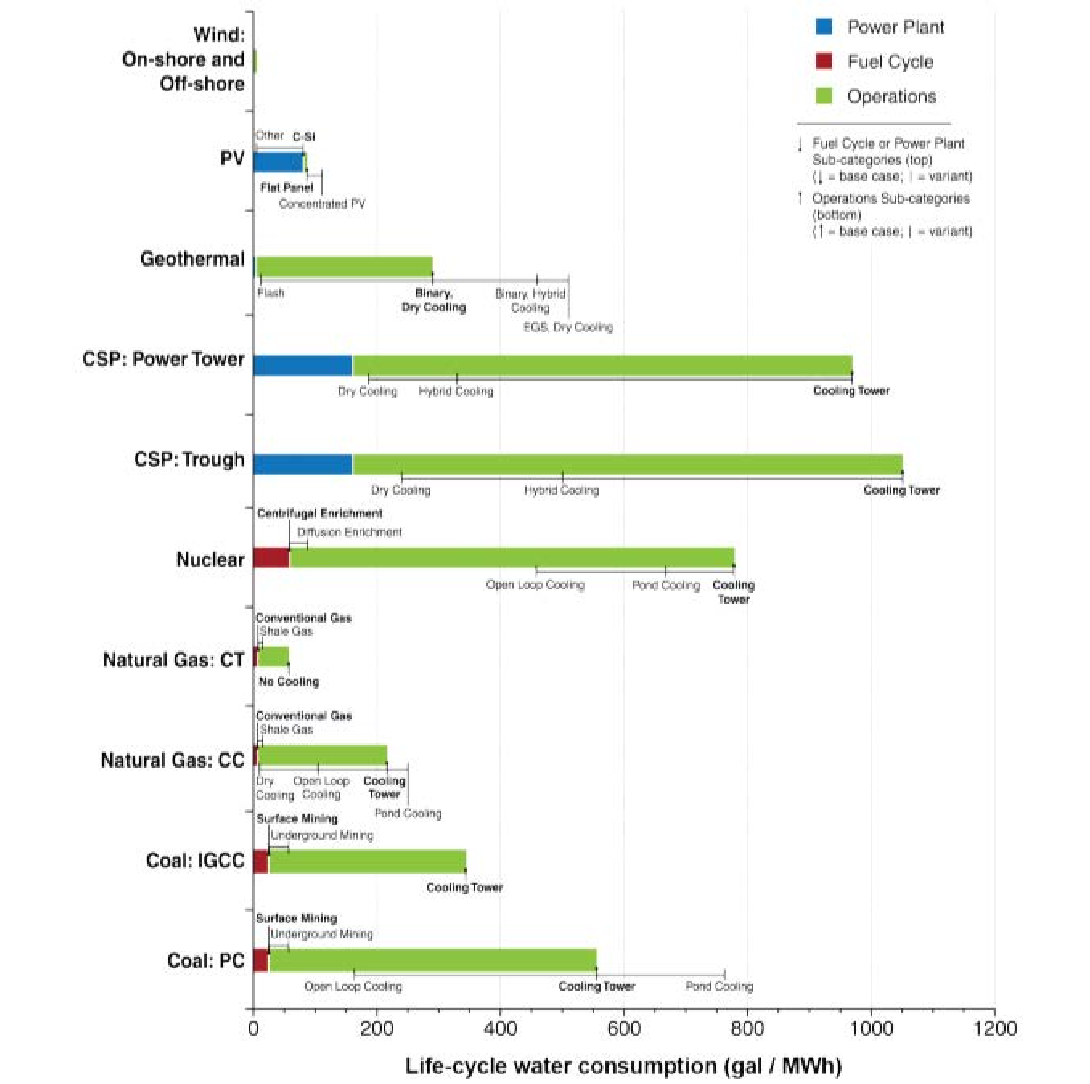
Materials (ton/TWh)	Generator only				Upstream energy collection plus generator			
	Coal	NGCC	Nuclear PWR	Biomass	Hydro	Wind	Solar PV (silicon)	Geothermal HT binary
Aluminum	3	1	0	6	0	35	680	100
Cement	0	0	0	0	0	0	3,700	750
Concrete	870	400	760	760	14,000	8,000	350	1,100
Copper	1	0	3	0	1	23	850	2
Glass	0	0	0	0	0	92	2,700	0
Iron	1	1	5	4	0	120	0	9
Lead	0	0	2	0	0	0	0	0
Plastic	0	0	0	0	0	190	210	0
Silicon	0	0	0	0	0	0	57	0
Steel	310	170	160	310	67	1,800	7,900	3,300

Key: **NGCC** = natural gas combined cycle; **PWR** = pressurized water reactor; **PV** = photovoltaic; **HT** = high temperature

Table 10.2 Representative Land Use Energy Intensity Estimates for a Variety of Electricity Generating Technologies[47] (Note that these estimates are from different studies and are not comparable as they use different assumptions for what is included and how it is included—i.e., they are not harmonized)

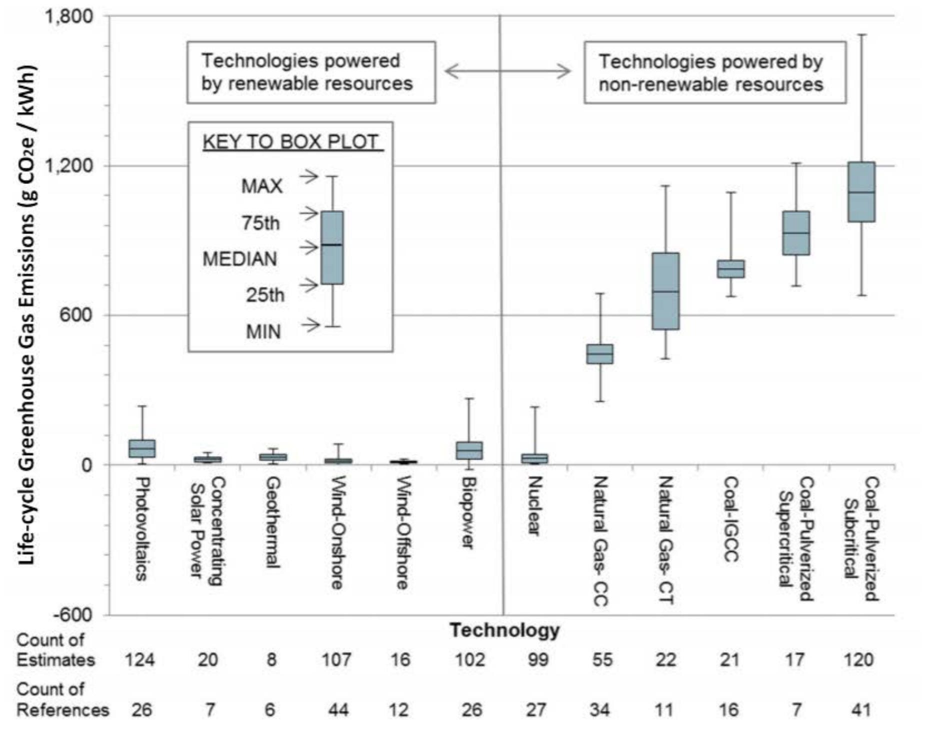
Energy technology	m^2/MW	System boundary Power plant site only; does not consider energy resource mining or collection, processing, or transport area, or land used for waste disposal
Biomass: direct-fired	9,000–45,000	Power plant site only
Coal	270–8,000	Power plant site only
Coal: CCS	12,000	Power plant site only
Nuclear	6,700–13,800	Low estimate is site only. High estimate includes transmission lines, water supply, and rail lines, but does not include land used to mine, process, or dispose of wastes.
Energy technology	**m^2/MW**	**System boundary Energy resource extraction area plus power plant site**
Biomass: gasification	3,000,000	Site and crop area. Area used primarily driven by biomass productivity and power plant efficiency.
Coal (site and upstream)	40,000	Site and strip mining included
Geothermal: hydrothermal	1,200–150,000	Low estimate is for the site only. Upper estimate includes well-field and plant.
Geothermal: hot dry rock	4,600–17,000	Includes well-field and plant
Hydropower: reservoir	20,000–10,000,000	Site of generators and reservoir
Solar: PV	10,000–60,000	Site of PV system, which includes the area for solar energy collection. PV systems on pre-existing structures have essentially no net increase in land use.
Solar: thermal	12,000–50,000	Site of concentrating solar thermal system, which includes the area for solar energy collection
Wind	2,600–1,000,000	Low-end value is for the site only, which includes the physical footprint of the turbines and access roads. The high-end value includes the land area between turbines, which is typically available for farming or ranching (see Section 10.5.7).

Figure 10.3 Life Cycle Water Consumption Estimates for Various Electricity Generation Technologies[44]



Notes: Not all cooling options are shown; for instance, more expensive, dry cooling (with zero water consumption and withdrawal) is an option for most plants. Key: **PV** = solar photovoltaic; **C-Si** = crystalline silicon; **EGS** = enhanced geothermal system; **CSP** = concentrating solar power; **CT** = combustion turbine; **CC** = combined cycle; **IGCC** = integrated gasification combined cycle; and **PC** = pulverized coal, sub-critical.

Figure 10.2 Illustrative Comparison of Life-Cycle GHG Emissions of Various Electricity Generation Technologies[32]



Note: Reference has "harmonized" original data to correct for differences in a number of input assumptions, resulting in reduced variance. "Count of estimates" refers to the number of separate sources of data. "Count of references" refers to the number of separate studies used to provide data. Key: **CC** = combined cycle; **CT** = combustion turbine; and **IGCC** = integrated gasification combined cycle.

Table 10.1 National Average Energy Efficiencies, Technology Shares for Each Fuel Type, and Criteria Air Pollutant Emission Factors (g/kWh) of the U.S. Power Sector in 2010[37]

Fuel type, combustion technology	Efficiency	Technology shares	NO_x	SO_x	PM_{10}	$PM_{2.5}$	CO	VOC
Biomass, ST	21.9%	100.0%	0.9267	0.603	2.814	1.9763	4.7546	0.1349
Coal, IGCC	34.8%	0.1%	0.1167[a]	0.0403[a]	2.4693	0.7198	0.02191	0.0012
Coal, ST	34.7%	99.9%	1.141	3.1998	0.2836	0.1994	0.1221	0.0147
NG, CC	50.6%	82.1%	0.1175	0.0041	0.0009	0.0009	0.098	0.0018
NG, GT	31.6%	5.5%	0.3452	0.0172	0.0386	0.0386	0.4458	0.0114
NG, ICE	32.8%	0.9%	3.0829a	0.0061[a]	0.4718	0.4718	3.8187	1.1102
NG, ST	32.3%	11.5%	0.8653	0.1745	0.0426	0.0426	0.4821	0.032
Oil, GT	29.4%	18.2%	2.9759	0.9438	0.3011	0.0763	0.0181	0.003
Oil, ICE	36.3%	4.6%	4.7442a	0.2274[a]	0.0138	0.013	0.0315	0.0119
Oil, ST	33.0%	77.2%	4.4825	7.6442	0.1797	0.1395	0.1676	0.0216

Notes: Plant-level (not life-cycle) emissions. Technology share is the ratio of the amount of electricity generated by each technology to the total electricity generation by fuel type. Key: **NO_x** = nitrogen oxides, **SO_x** = sulfur oxides, **PM_{10}** = 10 µm particulate matter, **$PM_{2.5}$** = 2.5 µm particulate matter, **CO** = carbon monoxide, **VOC** = volatile organic carbon, **ST** = steam turbine, **IGCC** = Integrated Gasification Combined Cycle, **NG** = natural gas, **CC** = combined cycle, **GT** = gas turbine, **ICE** = internal combustion engine.

[a] Adjusted based on averaged 2007 emission factors for coal IGCC, NG ICE or oil ICE as appropriate, and the 2007 to 2010 emission reduction rates of NO_x and SO_x for coal-, NG- or oil-fired power plants, respectively.

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The Shift Project

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

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Power system operation in energy transition scenarios

Technical file #7 – Draft version

Information and recommendations for scenario producers

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

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

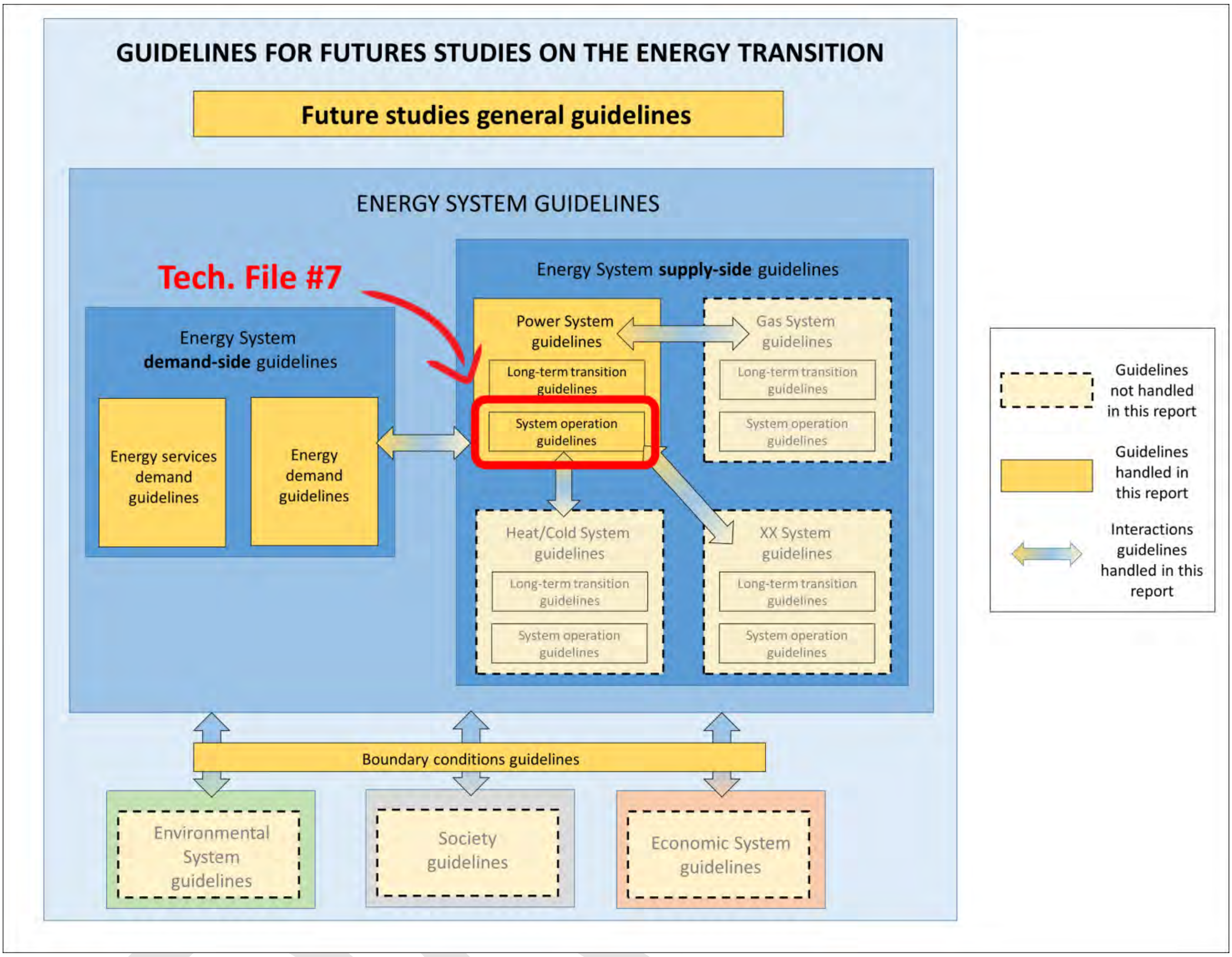
The goal of this project is to produce a set of guidelines addressed to scenario producers. These guidelines seek to foster transparency and consistency *within* future studies and to develop a common language *across* studies. By defining a number of important items which are key to deal with in future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

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

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

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

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



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

We warmly thank the experts who participated in this project by putting forward ideas and critiques, references and documents, and who accepted to discuss these ideas with us and other experts:

- Alexandre BARRÉ (UFE)
- Alain BELTRAN (Fondation EDF)
- Nicolas BERGHMANS (IDDRI)
- Michel BERTHÉLEMY (SFEN)
- Christophe BONNERY (ENEDIS)
- Sandra BOUNEAU (Institut de Physique Nucléaire d'Orsay - Université Paris Sud)
- Anne BRINGAULT (CLER-RAC-F)
- Julien BUEB (France Stratégie)
- Alain BURTIN (EDF)
- Jean-Michel CAYLA (EDF)
- Michel COLOMBIER (IDDRI)
- Emmanuel COMBET (ADEME)
- Patrick CRIQUI (Laboratoire d'économie appliquée de Grenoble)
- Dominique DRON (Ministère de l'Économie et des Finances)
- Robin GIRARD (Mines ParisTech)
- André-Jean GUÉRIN (The Shift Project)
- Emmanuel HACHE (IFPEN)
- Sylvain LASSONDE (Université Paris Saclay)
- Tanguy LE GUEN (ENGIE)
- Robert LOWE (University College of London)
- Arnaud MAINSANT (ADEME)
- Nadia MAÏZI (CMA)
- Teresa MADURELL (Institut de Ciències del Mar, Barcelona)
- David MARCHAL (ADEME)
- Yves MARIGNAC (Association négaWatt)
- Solange MARTIN (ADEME)
- Chloé MEXME (ENEDIS)
- Gilles MITTEAU (Chaîne Youtube Heu?Rêka)
- Thomas PELLERIN-CARLIN (Institut Jacques Delors)
- Jacques PERCEBOIS (Université de Montpellier)
- Dimitri PESCIA (Agora Energiewende)
- Gondia SECK (IFPEN)
- Laurent SCHMITT (ENTSO-E)
- Damien SIESS (UFE)
- Vera SILVA (GE Renewable Energy)
- Jordi SOLE (Spanish National Research Council, Madrid)
- Philippe TORRION (anciennement EDF)
- Eric VIDALENC (ADEME)

We also warmly thank the benevolent Shifters who helped us for the research for technical file #6 on the long-term evolution of the power system supply-side: Damien Ambroise, Sacha Bentolila, Fahd Boukrouche, Anne-Laure Delaye, Julien Kelder, Clément Le Priol, Arnaud Leroy, Alzargal Murat, Gaspard Pena Verrier, Félix Veith.

Table of content

Reading keys

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

Recommendations to scenario producers:

These boxes contain the recommendations for scenario producers.

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

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

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

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

I. System reliability is ensured by a set of key services

"Reliability of a power system refers to the probability of its satisfactory operation over the long run. It denotes the ability to supply adequate electric service on a nearly continuous basis, with few interruptions over an extended time period. Security of a power system refers to the degree of risk in its ability to survive imminent disturbances (contingencies) without interruption of customer service. It relates to robustness of the system to imminent disturbances and, hence, depends on the system operating condition as well as the contingent probability of disturbances. Stability of a power system refers to the continuance of intact operation following a disturbance. It depends on the operating condition and the nature of the physical disturbance." (IRENA, 2017)

Concretely, PS reliability is ensured by considering that the higher the probability of a failure, the lower its adverse consequences (which can be measured in undelivered MWs) must be[1] (RTE, 2004).

In Europe, countries have different ways to measure reliability, either through probabilistic assessment (in %) or through a deterministic one (yes or no). For example, in France, Belgium and the UK, a 3 hour/annum standard is set (corresponding to a 99.97% reliability). In other words, the objective is that nobody is cut from power during the whole year, except for three hours at maximum.

PS malfunction can be caused by:

- Consumption or generation variation
- Weather events (thunder, gale, frost, flood, hot or cold weather,...)
- Technical failures or aggression from outside
- Human mistakes in the operation or maintenance of the system

(RTE, 2004)

Such contingency events are driven primarily by factors independent of VRE-specific qualities, such as the loss of a large generator (renewable or conventional), transmission line or sub-station in the power system. The ability to return to a state of normal operation following a contingency event is referred to as "stability". While deployment of VRE does not necessarily influence the occurrence of contingency events, it changes the system's ability to remain stable (IRENA, 2017).

These events can lead to disturb some key electric parameters which must remain stable: frequency, voltage, and rotor angle.

- Frequency stability: Ability of a power system to balance active power that is, to balance generation and load (also called respectively supply and demand), which is equivalent to maintain frequency.
- Voltage stability: Ability of a system to maintain a steady state voltage at all bus bars, in normal operation or following a disturbance. This is equivalent to balance reactive power along the PS.
- Rotor angle stability: Ability of the synchronous machines in an interconnected power system to remain in synchronism after being subjected to a disturbance.

(BMZ Deutsche GIZ GmbH, 2013; IRENA, 2017)

These parameters, the consequences of their instabilities and their potential evolutions in scenarios are described in the following sections.

In order to control frequency, voltage and rotor angle synchronism, the architecture of the corresponding control system is composed of sensory organs, decision organs and actuation organs. These organs can be mechanical, electrical, electronical or numerical and they can be more or less concentrated on some equipment of the PS.

[1] This is known as the N-k rule

The fault[2] detection system supporting the PS and acting as its sensory organ for detecting faults must correctly operate for the PS to react fast enough to fix or isolate faults. Currently, generation units must provide enough fault current and be equipped with fault ride through capability for the detection system to operate correctly.

Finally, if frequency, voltage, or rotor angle control systems fail, this leads to a PS failure: local power outages, or total system blackout. In this case the PS must be able to restart as quickly as possible (which can take several hours to several tens of hours whereas minor control faults are solved within minutes to tens of minutes). This is the black start capability.

The different capabilities of the PS and its components enabling its proper operation are called ancillary services.

II. Frequency stability

A. Ensuring the balance between electricity supply and demand at all times: a matter of frequency

Frequency stability[3] reflects the fact that the global balance between supply and demand is achieved at all times. In case supply is lower than demand, spinning machines (also called synchronous machines) slow down hence system frequency decreases. On the contrary, if supply is greater than demand, spinning machines speed up hence system frequency increases (RTE, 2004).

Frequency variations can be caused by:

- Increase or decrease of supply
- Increase or decrease of demand
- faults of equipment, or human error, on the power system (e.g. the unexpected shutdown of a generation plant, or the disconnection of a high voltage line)

The consequences of frequency variations can be severe: inability to use the electricity vector if frequency is too different than 50 Hz (frequency reference value in Europe); damages to the electric devices plugged to the network; emergency shutdown of generation plants leading to total or partial power system collapse (RTE, 2004).

B. Flexibility is the ability of the PS to control frequency

The ability of the system to adapt to the variations of supply and demand is called *flexibility*. Downward flexibility is its ability to cope with increasing frequency (through production reduction or consumption increase, see Figure 1). Upward flexibility is its ability to regulate decreasing frequency (through increasing production or decreasing consumption). These frequency variations can be expected (e.g., expected increase of demand, or of production) or unexpected (Véronique Beillan, Caroline Bono, Sophie Bouly De Lesdain, & Fabien Bricault, 2018).

[2] Faults are short-circuits and insulation faults
[3] In alternative current (AC) power systems, electricity parameters oscillate at a given frequency, reflecting the frequency at which spinning machines producing, and consuming electricity, spin

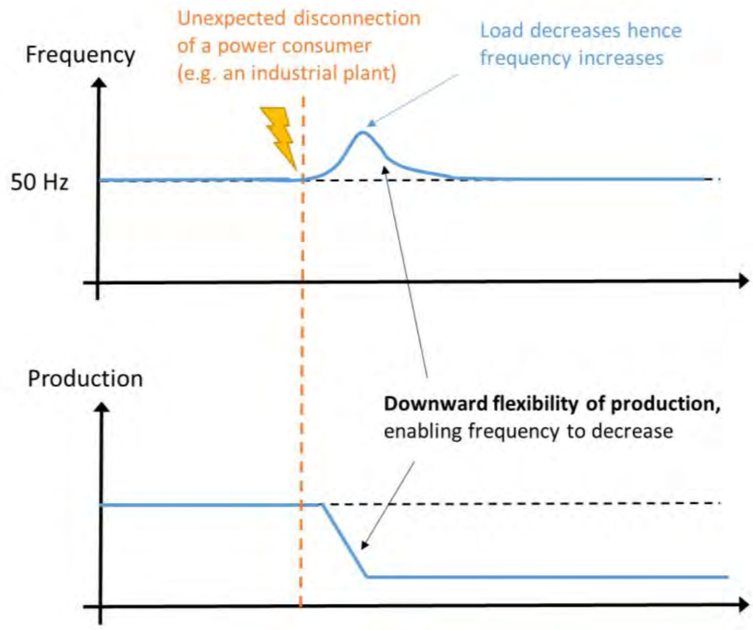


Figure 1: Illustration of downward flexibility lever activation following the disconnection of an important load (for example and industrial plant being disconnected). Source: The Shift Project.

Flexibility has two components (Véronique Beillan et al., 2018):

- flexibility needs: the need for flexibility comes from the uncontrollable variations of power demand or supply: consumption variations, RES variability, loss of production units or load disconnection.
- flexibility levers: they are the controllable variations of power demand and supply: controllable production units (flexible thermal – fossil fuel and nuclear – units, controllable RES), load management, storage and destocking, or call of the previous levers through interconnections. The grid, market design and operational processes must enable these levers to perform their flexibility roles.

In this section, we talk about flexibility assuming that total capacity is enough to meet demand. We only consider the dynamics of the supply to follow demand.

The verification of total capacity is considered in section about structural demand-supply balance (LTT)

Flexibility must be considered at different forecast horizons, depending on when it will potentially be needed. If flexibility is needed right away, only a few levers can be activated fast enough to fulfill the need. The further away in the future one looks, the more levers can be activated (some levers can be activated in a few minutes, other in tens of minutes, or hours…). However, flexibility needs evolve in the same direction: the further away in the future one looks, the more uncertainties there are about production and consumption, hence the more flexibility is needed in case these uncertainties materialize. As a result, flexibility is studied at different forecast horizons in order to make sure levers will always be available to cover uncertainties (Véronique Beillan et al., 2018).

C. A flexibility need for each forecast horizon

Flexibility needs can be categorized as follows, depending on their forecast horizon (Véronique Beillan et al., 2018):

- Inertia: this is the first response of the system to frequency variation. This response is due to its "natural" tendency to resist frequency change (see section on inertia below). The PS needs a high enough inertia in order for frequency not to change too fast in case an unexpected event happens.
- Reserves: reserves are an automatic or manual action at the production or load level in order to restore frequency stability and frequency value in a timely fashion, in case an imbalance happens. There is a need for a fast enough reaction time in order to counter frequency variation, and a need for enough capacity to restore frequency value.
- Daily flexibility (day-ahead or infra-day): this is the need for preparing a day-ahead plan for production, ensuring in a fine way that supply and demand will effectively match on the subsequent day, on an hour-to-hour basis. In most future studies, the term *flexibility* is used for infra-day flexibility.
- Weekly flexibility to season horizon flexibility: this is the need for preparing a rough production plan at the week to season scale.

- Constraints management for the grid (transmission and distribution): this is the need to plan several years ahead for the infrastructures and control devices that will enable to fulfill the future flexibility needs. These aspects are handled in section about long-term transition of power system.

D. Several kinds of levers to fulfill these needs

In order to fulfill these needs, flexibility levers exist. They can be gathered in four categories (Véronique Beillan et al., 2018):

- Conventional power generators: for fast action (a few minutes), they can modify the power they deliver, in an upward or downward direction if their operating point is not already at its highest or lowest and if they are already started. For slower action (tens of minutes for hydropower and a few hours for thermal power generators), conventional generators can be started or stopped. Thermal generators currently fulfill most of the flexibility needs. Some technological evolutions in nuclear power and in natural gas turbines could enable an increase of their flexibility.

- Load management and demand response within the industry sector, tertiary sector, or housing sector: this kind of flexible load is already able to provide flexibility services (reserves acting on the load side). Load management gathers three levers:

    - load shedding: consumer decides to cancel its consumption for a short time. This decision can be locally compensated by the use of another source of energy (for example a fuel engine-generator).

    - load delay: load is automatically delayed (such as for French storage water heaters)

    - demand turn up: consumers are asked to turn up their consumption. This service is asked in case of extreme downward flexibility needs.

  Load management capacity depends on market rules and regulations which determine the interest a consumer has to accept a management of her consumption. The development of load management depends on its competitiveness against other means to ensure grid constraint management and on the evolution of technologies enabling load management.
  Demand response is based on the behavior of consumers in reaction to live price signals. The ability of consumers to react to price signals depends on the information they have about their consumption and the prices. Hence with proper incentives, price signals can be organized such as to provide flexibility services.

- Storage devices, in particular hydro power (traditional or pumped-storage) or electrochemical storage (batteries), can provide flexibility services. Storage can provide downward flexibility (by storing up energy) and upward flexibility (by injecting electricity). The different flexibility services it can provide depend on the type of storage through its key characteristics: energy capacity and power capacity, as well as swear patterns. Storage can also participate in grid constraint management. However, electrochemical storage is not economically competitive yet compared to a solution based on RESV curtailment (ensuring downward flexibility at low cost) and CCGT (ensuring upward flexibility at low cost, even with a carbon price). This situation depends on the market design and the revenues for different flexibility services. EVs, as storage devices, can participate in flexibility services.
  Similarly, P2X technologies[4] can participate in flexibility services.

- Variable Renewable Energy Sources (VRES, composed of photovoltaic systems (PV) and wind turbines): they could provide flexibility services with proper adaptation of their inverters (see below). However their variability limits their ability to do so and requires good forecasting capabilities. RESV curtailment is a downward flexibility which should be taken into account when designing the PS, as an alternative to grid reinforcement (grid constraint management).

E. Different markets for infra-day to season forecast horizons

The day-ahead market is the mechanism through which electricity bulk prices are set for each hour of the day ahead. This market gathers electricity producers and electricity bulk buyers. It sets the day-ahead production plan of electricity producers taking into account the inertias of the different elements of the PS.

[4] P2X is the set of processes converting electricity in another potential energy which can be stored: power to heat, power to gas, power to fuel, power to products or power to liquids (Véronique Beillan, Caroline Bono, Sophie Bouly De Lesdain, & Fabien Bricault, 2018)

Closer to real time is the infra-day market. This market enables buyers to modify their positions given contingencies which appeared since their latest day-ahead position.

Further away from real time is the futures market. Futures market enable actors to buy or sell energy for a given future period of time, with a price fixed in advance (Véronique Beillan et al., 2018).

Longer-term flexibility (at the scale of several years) is ensured by studies leading to proper investments in flexibility levers. Such studies can be led if proper incentives to do so are in place (for example, a proper market design should give incentives to invest in flexibility levers if flexibility needs increase) (Véronique Beillan et al., 2018).

F. Inertia and reserves are key for flexibility real-time management

1. Inertia: the physical tendency of the PS to resist to frequency changes

Inertia is a technical term that describes the ability of a power system to resist changes in frequency.

Inertia is an inherent property or characteristic of each generator and element of load that is on-line and *coupled directly* (as opposed to electronically coupled) to the interconnection. The inertia of the PS is the sum of the combined inertias of all the connected generators and loads (Eto, Undrill, Roberts, Mackin, & Ellis, 2018).

Conventional synchronous generators (or Synchronous Machines, SMs), as well as rotating load devices include a turbine system and rotating components exhibiting mechanical inertia, and as such they are capable of storing kinetic energy in this rotating mass. Because that energy can be extracted from or absorbed into these rotating masses during system disturbances, an interconnected system of machines is able to withstand fluctuations in net load and generation. For example, reducing the speed of a nuclear plant 1.6 GW alternator from 1500rpm to 1470rpm requires the same amount of energy as stopping 22 40-tons trucks running at 100km/h[5] (Véronique Beillan et al., 2018).

Load significantly participates in inertia. As a consequence, if load evolves to more electronically coupled engines instead of directly coupled motors, PS inertia will decrease[6] (Eto et al., 2018).

2. Reserves: the controlled reaction of the PS to counter frequency changes

The main close-to-real-time flexibility capacities of the system are called reserves. Their objective is to handle strong balance variations which are not forecasted by day-ahead or infra-day plans (for example subsequently to faults on production units, forecast mistakes, variations of RES production or of consumption, or several at the same time, see section on reliability).

Reserves are composed of:

- Frequency Containment Reserve (FCR, ENTSO-E naming), or primary reserve, automatically triggering action in participating plants (or consumers) within a few seconds. Its goal is to restore the production-consumption balance, stabilize the frequency and limit its fall (or rise). In the European power system, the upward FCR must represent 3 000 MW, which corresponds to the power of the two biggest power units.
  In case inertia is not high enough, a very fast reaction to frequency variation should be automatically triggered (within a second or so) at production or load level. This emerging need is called Fast Frequency Containment Reserve (Fast FCR)[7].

[5] Inertia in the European PS is between 20 and 30 mHz/s (this frequency variation rate is called rate of change of frequency). In other words, if a synchronous generator is suddenly disconnected, the global frequency of the PS does not decrease faster than 30 mHz/s. (Véronique Beillan et al., 2018)
[6] Directly coupled motors "slow down" when frequency declines and reduce power consumption, and thereby work in concert with FCR delivered by generators. By not slowing down and not reducing power consumption, electronically coupled motors no longer contribute or support FCR delivered by generators.
[7] A few PSs are already calling for larger Fast FCR, such as the PJM network in the North East of the US or National Grid UK

- Automatic Frequency Restoration Reserve (aFRR), or secondary reserve, enabling to restore the frequency to 50 Hz and the exchanges through interconnections
- Manual Frequency Restoration Reserve (mFRR) and Replacement Reserves (RR), or tertiary reserve. They are manually activated in order to replace the preceding reserves and get back to the initial reserve situation. (Véronique Beillan et al., 2018)

A key moment in the control is when FCR takes over when frequency starts to drop. The speed at which it must react depends on the system inertia: the lower the inertia, the faster the FCR must be in order for frequency not to drop too low[8] (Eto et al., 2018).

If frequency drops too low, rolling blackouts[9] are triggered. If frequency changes too fast or spikes too high, many equipment of the power system are automatically disconnected, which might lead to blackouts. (Véronique Beillan et al., 2018)

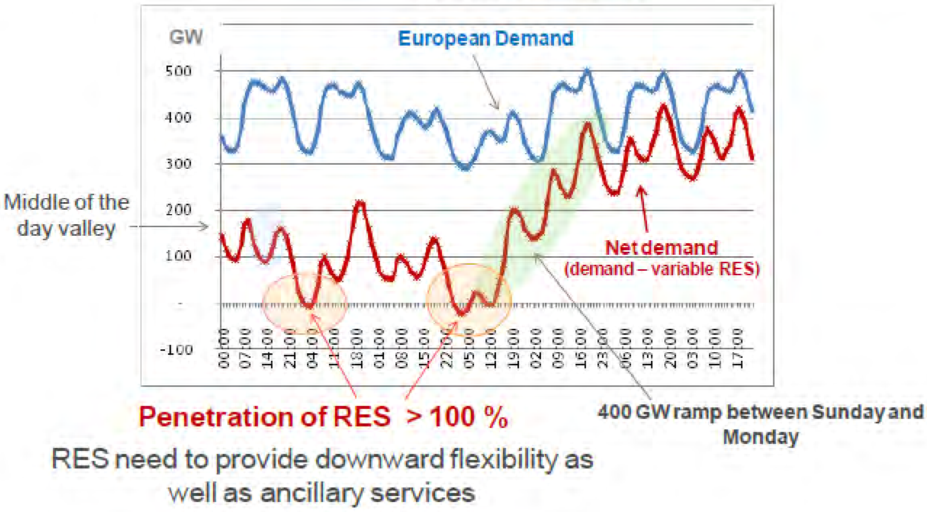
G. Greater shares of VRES impact flexibility needs at several forecast horizons…

The evolution of PSs in scenarios may lead to issues about flexibility needs. These issues have emerged through the observation of lowly interconnected power systems with rising shares of VRES, such as the Irish (Eirgrid) or Texan (ERCOT) ones.

For scenarios implementing a growing share of VRES, flexibility needs evolutions can be expected. Simulations of the European PS with a 60 % share of RES run by EDF led to the following conclusions (EDF, 2015):

- VRES variability impacts season to infra-day horizons flexibility needs.
  - At day to infra-day horizon, the greater the VRES share, the shorter the duration of flexibility needs, but the greater their magnitudes. Also, with more VRES, the more often they will produce in excess, hence the more often downward flexibility will be required (see Figure below, source (EDF, 2015)).

FIGURE 10 : LOAD-GENERATION BALANCING BECOMES QUITE COMPLEX FOR PERIODS WITH HIGH NET DEMAND VARIABILITY



  - At season horizon, the more VRES, the more inter-season flexibility will be required. Indeed, in Europe VRES tend to produce in excess in spring and summer but produce too little in winter.

The larger the geographical perimeter of the PS, the lower the variability of production at global scale (aggregation effect). Wind and PV generation present an intermittent generation profile at site level but as a result of natural geographical diversity this intermittency can be reduced when total production is

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[8] The key factors determining the lowest value of frequency in case of a frequency drop are (a) the effective inertia constant of the system, which determines the initial rate of decline of frequency; and (b) the rate at which generation is increased by FCR response

[9] Intentionally engineered electrical power shutdown where electricity delivery is stopped for non-overlapping periods of time over different parts of the distribution region

considered at regional or national level. However, wind regimes are often somewhat correlated across Europe. Thus at the European system level a significant variability in the output of wind generation as a function of atmospheric conditions is observed. Conclusions are similar for PV (EDF, 2015).

- VRES uncertainty impacts reserves needs. VRES rely on weather-related energy. The more VRES in the PS, the more the production relies on weather events, hence the greater the uncertainty about production. This uncertainty is reduced when weather forecast accuracy is improved. It is also reduced when the geographical perimeter of the PS is larger. Indeed chances are low that uncertainties of local productions all materialize as forecast mistakes at the same time and in the same direction. In other words, local uncertainties taken together in one interconnected PS do not add up.
- Inertia decreases with more power electronics inverter connected plants, as VRES. Nowadays the spin of a wind turbine is disconnected from the frequency it injects on the grid through the inverter, in order to optimize its power production (Véronique Beillan et al., 2018). By nature, PV power is not produced through a spinning machine and is connected through inverters (BMZ Deutsche GIZ GmbH, 2013; Kroposki et al., 2017). Inertia issues appeared on ERCOT power system in Texas (Matevosyan, 2017) and on Eirgrid in Ireland (O'Sullivan, Power, & Kumar, 2013), leading to curtailing VRES production in order to ensure a minimal level of inertia.

A decrease in inertia may be counterbalanced by a faster FCR. Hence a need for faster FCR could appear in scenarios with a high share of VRES (Véronique Beillan et al., 2018).

H. **… But** can also partly constitute, and benefit from, new flexibility levers

As flexibility needs may evolve in some scenarios, new flexibility levers can be introduced in order to fulfill these needs. Here is a review of the different technologies which could be used as flexibility levers.

1. Inertia can be provided by synchronous machines and by synchronous compensators whereas VRES and batteries can provide fast FCR

A first, conventional solution to tackle the insertion of more VRES is to ensure there is always enough inertia in the system, at each moment in time, by keeping a minimal amount of Synchronous Machines. However, this could lead to maintaining high-emissions, or high-costs plants running or to VRES curtailment.

A low-cost option to maintain inertia is to install synchronous compensators (see Figure 2), which are synchronous machines running without producing electricity. They are useful to bring their inertia to the system (Véronique Beillan et al., 2018). They can provide all the ancillary services of conventional generators except those requiring active power, i.e. they can provide fault current, inertia and voltage support (see following sections) just like a synchronous generator. (Brown et al., 2018)

Figure 2: a synchronous compensator at Templestowe substation, Melbourne Victoria, Australia (source: Wikimedia Commons)

Another lever to help power systems with decreasing inertia is to connect VRES through Virtual Synchronous Machines (VSM) inverters (grid-forming). In these inverters, a set of algorithms enable it to mimic the physics and control laws of Synchronous Machines (SMs) in terms of stability (Véronique Beillan et al., 2018)

With VSM connections, wind turbines can contribute to fast FCR for a limited amount of time (about 5-10 seconds), by suddenly reducing rotor's speed and transforming the corresponding kinetic energy into electric energy[10] (Eto et al., 2018). However, this requires that wind turbines be producing when the need for inertia appears.

Similarly, electric batteries can provide such a response when batteries are not empty (Kroposki et al., 2017).

Technically though, the response of VRES with VSM inverters is very fast FCR rather than inertia (see next section): if total inertia from Synchronous Machines becomes very low, VSM responses can become too slow in case of frequency variation, leading to PS instability (Véronique Beillan et al., 2018).

Furthermore, economically speaking, headroom should be allocated to conventional power plants because variable costs of wind and solar are virtually zero.

If it happens that wind and solar penetration levels become extremely high additional storage devices could be installed, only for the purpose of providing active power capacity to the system for inertia simulation and for reserves (BMZ Deutsche GIZ GmbH, 2013).

2. Faster FCR is cost-efficiently provided by batteries, and by VRES curtailment for downward FCR

Faster FCR can be provided by several means: storage (batteries, inertial storage…), VRES, load… However nowadays batteries seem to be the most cost-competitive solution, as illustrated by the solutions proposed for a 200 MW fast FCR call by National Grid UK: out of 64 proposals, 61 were for batteries.

As previously developed, PV and wind turbines can easily provide fast FCR when production must be decreased, by electronically curtailing production. They can also provide fast FCR when production must be increased, if they keep some headroom and if the event happens when they produce. In other words, they have to be permanently and significantly curtailed to provide this service (Véronique Beillan et al., 2018). Here again, for economic reasons, this service could be more efficiently provided by extra storage devices (BMZ Deutsche GIZ GmbH, 2013).

Thus VRES controllers, if carefully designed and under the previous conditions, can provide primary response that is faster to the response from conventional generators because of the fast-response speed from the power electronics interfaces (Kroposki et al., 2017).

[10] This fast FCR capability is sometimes improperly referred as "synthetic inertia"

I. A challenge for future studies: properly estimating flexibility balance with large shares of VRES

As developed above, modeling challenges arise for scenarios implementing large shares of VRES, as they largely modify flexibility needs and also partly constitute levers. We reviewed how future studies tackle this challenge as of today.

1. Future studies consider season to infra-day flexibilities, but simpler methods cannot properly represent the effects of large shares of VRES

Most future studies we reviewed ensure that season to infra-day flexibility needs are fulfilled by flexibility levers. Two main methods are used to do so:

- The computationally lighter method is to define a few "time-slices" within the year and simulate what happens in these time slices (IRENA, 2017). They usually are one-, or two-hour slices representative of the different load and generation patterns within the year. Typically, slices represent a day for each season in order to account for load variation with seasons. Assumedly, if the power system correctly operates over these time slices, it does so at any time. This method is particularly efficient for modeling power systems whose operation can be finely represented by a little number of exemplary conditions. The more variable generation in the power mix, the greater the number of different conditions it undergoes, hence the less adapted this method. In order to check the balance between load and production, an estimate of VRES production is produced. This estimate is based on a *capacity credit* which is allocated to the different VRES technologies. This credit represents an average capacity (over the installed pool of the considered technology) modelled as guaranteed for different types of loads (baseload, mid-load, peakload…). For example, a model can allocate a peakload capacity credit of 10 % for wind turbines, meaning that 10 % of the installed capacity is considered as available at peakload time. Then dispatchable production is computed. This method is used by POLES model (Keramidas, Kitous, Schmitz, European Commission, & Joint Research Centre, 2017), PRIMES model (E3Modelling, 2018), and was used by the WEM before 2016 (International Energy Agency, 2018).
- The previous method can be improved so as to represent and simulate load and supply for all the one-hour time slices of each year. In other words, this method uses an hourly time step (that is, 8760 one-hour time-slices). It better represents variable renewable power generation, as it simulates a greater diversity of weather patterns. Many studies we reviewed use this method (ADEME, 2012; Association négaWatt, 2014; ECF, 2010; Fraunhofer ISE, 2015; NégaWatt, 2017; OECD/IEA, 2017). Some studies go further and simulate several years of weather pattern for each state of the power system during its transition. This allows to further test the robustness of the power system to different weather patterns, especially to rare and extreme ones. The weather data can be the exact reproduction of measured weather data in past years (such as in (ADEME, 2015; ADEME / Artelys, 2018; Agora Energiewende, IDDRI, 2018)), or it can be simulated to stochastically generate realistic weather data (as is performed in (RTE, 2017)). In the latter case, weather data including climate change effects can be simulated.

2. A few future studies consider reserves, very few properly represent the effects of large shares of VRES

Some future studies take into considerations reserve needs and reserve levers in their modeling, checking the balance between them. Traditionally, in power systems based on dispatchable units, ensuring a given amount of reserve margin (that is, extra capacity which would be available above peak load) was enough to tackle the largest uncertainty (which was estimated using the worst realistic fault which could occur). The difficulty for models implementing large shares of VRES is to model the uncertainty of VRES production, which leads to greater reserve requirements.

Only a few models perform such uncertainty estimation (such as METIS model by ARTELYS (ARTELYS / European Commission, 2016; ARTELYS / European Commission, 2017) or the Dynamic System Investment Model from Imperial College (ECF, 2010; Imperial College London, NERA, DNV GL, 2014)). They do so by modeling VRES expected production and actual production, hence modeling for each hour of the year the gap between "forecasted" VRES production and "obtained" VRES production. One method is to simulate "forecasted" production by using databases of historically forecasted weather and deducing from them what the production forecast was at that time. Another method is to stochastically generate the "actual" production, hence modeling the weather uncertainty.

3. The few future studies considering inertia do so **"manually"** (without modeling it)

Inertia is rarely considered in future studies. In the cases it is considered, the amount of synchronous production is evaluated at each hour of the simulation (hence only models using an hourly time-step can perform it), and compared to exogenous thresholds. A static threshold can be used (e.g. ENTSO-E claims that 150 GW of spinning production must be operating at any time within the Wester Europe power system in order to ensure an appropriate minimal level of inertia), as is done in (RTE, 2017). Alternatively, a dynamic power threshold can be used in order to take into account the fact that power load level varies with time (indeed, for low loads the static threshold might be oversized). The ratio of non-synchronous generation over total generation ("System Non-Synchronous Penetration") is computed at any time and must not get above a fixed threshold. For example, Eirgrid, the Irish Transmission System Operator accepts 65 % of System Non-Synchronous Penetration (ADEME / Artelys, 2018).

However, the inertia of load (that is, inertia of spinning devices which consume the electricity) has to be considered: simulations showed that the lower the load, the greater the required amount of system synchronous penetration (EDF, 2015). Inertia of the load is not considered in the future studies we reviewed. This may lead to biased estimates of inertia requirements. E.g. too loose dynamic thresholds may be used for low load levels. In addition, load could significantly evolve during the transition, affecting inertia requirements: if load evolves to more electronically coupled engines instead of directly coupled motors, PS inertia will decrease[11] (Eto et al., 2018).

J. A summary of flexibility levers and the needs they can fulfill

Below is a table summarizing the already available, and potential flexibility levers against the needs they can each fulfill (Véronique Beillan et al., 2018). Storage technologies, hydropower, dispatchable biomass, as well as thermal production and flexible consumption can fulfill both upward and downward flexibility needs as long as no saturation effect applies (for example, some storage energy capacity might be empty, some thermal power units might already be operating at its highest point, or no flexible consumption offer is available at a given time). VRES with Virtual Synchronous Machines inverters (VSMs) can provide downward flexibility through curtailment, and upward flexibility only if they operate with headroom. In both cases, they must be producing power to be flexibility levers. Furthermore, as primary, secondary and tertiary reserves need to be sustained for a given amount of time before replacement reserves restore them, the associated flexibility levers must be sustained for several minutes, which may not be the case of VRES production.

[11] Directly coupled motors "slow down" when frequency declines and reduce power consumption, and thereby work in concert with FCR delivered by generators. By not slowing down and not reducing power consumption, electronically coupled motors no longer contribute or support FCR delivered by generators.

<table>
<tr><th></th><th colspan="7">System needs</th><th>Grid needs</th></tr>
<tr><th></th><th>Season flexibility</th><th>Week flexibility</th><th>Day / infra-day flexibility</th><th>mFRR + RR</th><th>aFRR + FCR</th><th>Fast FCR</th><th>Inertia</th><th>Grid constraints</th></tr>
<tr><td rowspan="4">Storage</td><td></td><td></td><td colspan="4">Batteries</td><td></td><td>Batteries</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td colspan="2">Fly wheels</td><td></td></tr>
<tr><td></td><td colspan="7">Pumped hydro</td></tr>
<tr><td></td><td></td><td colspan="3">Compressed air</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Thermal production</td><td colspan="5">Thermal power (nuclear and flame)</td><td></td><td>Thermal power</td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="2">Engine generator</td><td></td><td></td><td>Engine generator</td></tr>
<tr><td rowspan="5">RES</td><td colspan="2">Large hydropower</td><td colspan="5">Hydropower</td><td>Small hydropower</td></tr>
<tr><td></td><td></td><td colspan="4">Wind farms (with VSM)</td><td></td><td>Wind farms</td></tr>
<tr><td></td><td></td><td colspan="4">PV farms (with VSM)</td><td></td><td>Small PV</td></tr>
<tr><td></td><td></td><td colspan="6">Concentrated solar power</td></tr>
<tr><td></td><td></td><td colspan="6">Dispatchable biomass</td></tr>
<tr><td rowspan="5">Flexible consumption</td><td></td><td></td><td colspan="4">Evs (load management and V2G with VSM)</td><td></td><td>Evs</td></tr>
<tr><td></td><td></td><td colspan="2">Smart appliances</td><td></td><td></td><td></td><td>Smart appliances</td></tr>
<tr><td></td><td></td><td colspan="3">Cold/ heat in housing and tertiary</td><td></td><td></td><td>Cold/ heat in housing and tertiary</td></tr>
<tr><td></td><td></td><td colspan="3">Industrial load management</td><td></td><td></td><td>Indust. load management</td></tr>
<tr><td>Power2X (Gas, liquids, H2…)</td><td></td><td colspan="3">Power2X (gas, heat…)</td><td></td><td></td><td>Power2X (gas, heat…)</td></tr>
<tr><td rowspan="2">Flexibility devices</td><td></td><td></td><td></td><td></td><td></td><td></td><td>Synchronous compensator</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>Rotating load</td><td></td></tr>
</table>

Figure 3: already available, and potential flexibility levers against the needs they can each fulfill (Véronique Beillan et al., 2018). Reading key: Storage technologies can provide different services of flexibility. For instance, fly wheels can provide fast FCR and inertia.

K. The larger the PS, the lower the flexibility needs

At all forecast horizons, increasing the geographical perimeter of the PS in addition to ensuring a proper centralized control of flexibility levers leads to a reduction in flexibility needs through aggregation effect. (Véronique Beillan et al., 2018)

L. Are smart grid technologies flexibility levers?

New smartgrid technologies, such as new grid forecast management solutions[12], advanced control functions and smart meters represent opportunities to manage flexibility needs at global and local scales. However, a local management of flexibility needs could lead to a suboptimal global management. The effects of local management of flexibility is still under study. In all cases, local management requires a close partnership between TSOs and DSOs (Véronique Beillan et al., 2018).

Recommendations on dynamic demand/supply balance

A scenario strategy about frequency management and flexibility should be defined and justified. It should include considerations on the decision to study dynamic demand/supply balance or not. This strategy depends on the Planning Question and on the study overall strategy.

If the strategy is to discard this aspect, a qualitative analysis of the limitations it induces in the study should be performed.

The different aspects of flexibility which are considered should be reported, and their link to the study strategy should be outlined.

[12] Forecast and simulation tools based on a closer monitoring of distribution grid enabling to avoid reinforcement works and to optimize production (ENEDIS, 2016)

Hereunder are aspects of flexibility which may be reported about. These aspects are impacted by the overall structure of the PS and the level at which frequency is controlled (local level/ national level/ continent level…).

Questions in italic are examples to illustrate the aspects which are dealt with.

- Considered categories (forecast horizons) of flexibility needs should be made transparent. *For example: What forecast horizons are considered in the scenario for evaluating the balance between needs and offer? In what respect is it useful to consider these horizons and not others with regards to the study strategy?*
- Considerations on the coverage of the flexibility needs by the levers during the tested years, and on the indicators to convey this information, such as: is the obtained lever mix sufficient to cover the considered needs? If not, what are the impacts? These considerations should be provided for all the forecast horizons which are considered in the scenario. *For example: over the set of considered test years, are the needs fulfilled by the proposed levers' mix? If not, how often is the mix insufficient? What are the impacts of the insufficiencies on public perception, on economic criteria…? What would be the main trade-offs to consider to get a better coverage in the scenario?*
- Overall methodology used to assess the level of demand and supply balance for the different forecast horizons which are considered in the study. For example, a methodology to assess inertia level is proposed in (Krakowski, 2018).

The following aspects may be detailed for a greater level of transparency. Dealing with those aspects should not require extra core work if the previous aspects have been presented. However, they require extra work for popularization and final editing.

- Time pattern of levers' activations through the year and for each considered forecast horizon; activation mechanisms if they significantly differ from current ones. *For example: When, and how much, is the wind production curtailed? When do wind turbines participate in upward flexibility?*
    - o In particular, day-ahead to infra-day activation patterns are sometimes extensively described in scenarios (hour-per-hour description of power production and consumption, including storage pattern). A strategy about day-ahead activation patterns should be explicited.
      The following aspects could be described: Load, power generation, storage (consumption and production), demand-response and load management.
      Those aspects can be described per technology (or another disaggregation level depending on the driving questions), per region (or another resolution depending on the driving questions), and/or per type of actor. For example, demand-response activation could be described per type of actor (industry, households…).
      Other indicators could be provided, such as loss indicators (*how much loss, including curtailment, for each tested year?*); full load equivalent operating hours for production units, transmission load factor for relevant lines, or power import/export indicators.
- Available flexibility levers with regards to the technological storyline, for each considered forecast horizon. *For example: What levers are considered in the scenario (batteries, thermal power units…)? In the scenario time frame, when does each of them start to be available? Is it consistent with the technological storyline?*
- Characteristics of flexibility levers, such as operating constraints (ramp up and ramp down capabilities, minimal or maximal operating points…), their costs, their impacts on society, how society adopts them (acceptance), or the environment, etc. *For example, depending on the study strategy: what are the characteristics of batteries with regard to flexibility (energy capacity, power, life duration as a function of use…)? How much lithium is required for the production of one battery?*
- Evolution of these characteristics through the scenario. The origin of these evolutions: technological (for conventional generators, storage devices and VRES) and / or behavioral (for load management and demand response). *For example: Do cost, technical characteristics and resource consumption of batteries evolve through the scenario? If yes, what does explain these evolutions?*

- Flexibility markets, for different forecast horizons. *For example: What are the considered market incentives for developing flexibility levers in the scenario? Are there any evolution of the flexibility market in the scenario?*
- Flexibility needs evolution through the scenario, such as: the total capacity for each considered forecast horizon, the frequency at which the need appears, the emergence of new flexibility needs. These needs depend on the weather-dependent share of production and on weather forecast performances. *For example: What evolution of the need for inertia during the scenario timeframe? Does a need for Fast FCR appear during the scenario timeframe? What evolution of the need for reserves? What evolution of the frequency of call of reserves?*
- Evolution of flexibility levers capacities per type of lever; geographical locations of the levers. *What evolution of the number of PV farms with VSM inverters in the scenario? What evolution of the installed capacity of such farms? Where are these farms located?*

M. Greater shares of inverter-connected plants lead to lower quality electrical waves

For the AC to DC transformation, inverters used to connect PV and wind turbines to the grid produce electrical waves which are not perfect 50 Hz sine waves. Instead they contain some upper frequency waves, in the 0 kHz to 2 kHz range (harmonics) when produced by older inverters. These harmonics can disrupt the operation of some devices and accelerate the aging of electrical insulants.

New inverters use faster mechanisms hence they produce different, but still imperfect sine waves containing higher frequency waves (greater than 2 kHz). Furthermore, each inverter emits different types of waves depending on its operating point and on the local voltage at its connection with the grid. The effects of those waves are the same as harmonics if their magnitude is too high.

These waves can be damped by installing filters, which induces extra-costs.

However, their variety and complexity make simulation and forecast studies about them difficult. More research is needed to evaluate the extra-costs of damping as necessary these waves (Véronique Beillan et al., 2018).

Recommendations on sine waves quality

A scenario strategy about sine wave quality should be defined and justified. It should include considerations on the decision to study this subject or not. If the strategy is to discard this aspect, a qualitative analysis of the limitations it induces in the study should be performed.

This strategy depends on the Planning Question and on the study overall strategy. The different aspects of it which are considered should be reported, and their link to the study strategy should be outlined.

The following aspects may be reported about:

- Evolution of the quality of the sine wave through scenario timeframe
- Overall methodology to assess this quality
- Impacts and induced costs if sine wave quality is inadequate

The following aspects may be detailed for a greater level of transparency. Dealing with those aspects should not require extra core work if the previous aspects have been presented. However, they require extra work for popularization and final editing.

- Evolution of the level of harmonics emissions, determined by the amount and type of power electronics devices connected to the grid
- Evolution of the level of damping, determined by the quantity of installed damping filters, and associated costs

III. Voltage control

A. Voltage: a decentralized parameter which must be controlled locally

Voltage is the parameter in a power system that indicates whether there is a reactive power[13] imbalance in an area of a system (BMZ Deutsche GIZ GmbH, 2013).

Voltage is maintained around different values with different confidence intervals for the transmission grid and the distribution grid. Indeed the functions of these networks are different: the transmission grid must reduce losses and preserve stability (requiring high voltages); the distribution grid must finely tune the voltage for the end-consumer so that all her equipment operates (requiring a tight confidence interval on voltage) (Véronique Beillan et al., 2018).

Voltage evolves through time following supply and demand variations as well as grid topology variations. At a given time, voltage evolves through space as a function of the topology of the connected equipment and plants (RTE, 2004). Space evolution reflects reactive power production and consumption. Lines consume reactive power, hence reactive power decreases with the distance to its source.

Voltage should be maintained around its nominal value at all points of the system.

Equipment connected to the grid as well as power plants require the voltage to be maintained around its nominal value. Indeed these equipment are designed to operate for contractual voltages. Equipment can be worn or damaged if it is too high. If it is too low, intensity can become too high for lines. Low voltage can induce transformers and power plants malfunctions as well as making the operation of the grid more difficult (RTE, 2004).

A low voltage problem can lead to a system-wide collapse, for example several minutes or hours after a big power plant has unexpectedly disconnected (BMZ Deutsche GIZ GmbH, 2013).

Finally, voltage control is required to control power imports and exports through interconnections.

B. Current voltage control: several organs organized in a complex architecture distributed over the grid

Voltage stability can be decomposed within two components:

- Static voltage stability is the maintenance of local reactive power balance during normal operation of the system.
- Dynamic voltage stability is the ability of the system to absorb disturbances. This ability is mostly driven by the short circuit current delivered during a disturbance. This topic is developed in Section about short-circuit current. The current section is about static voltage stability only.

Reactive power decreases with travelled distance. Hence it is more efficient to correct voltage variations very close to consuming devices (that is, at the level of distribution grid). However, control at the transmission grid level is required as it provides the frame within which the distribution grid operates. Control capabilities are also installed at the interface between the two grids through tap changers[14], and then in the distribution grid through passive devices (capacitors).

At the transport grid level, conventional generation plants provide a voltage control capability, each up to a certain point. Hence they are a simple and efficient lever for voltage control. In Europe, this service is remunerated through contracts with TSOs, or is regulated by law in order to get connection clearance (Julia Merino, Inés Gómez,

[13] Reactive power is not a power per say. It is expressed in volt-ampere reactive (var). It appears in electrical components containing capacitors or self-inductance, as they produce a phase gap between the voltage wave and the current wave. In these cases, a part of the current creates a magnetic field which is not used for mechanical work but leads to extra losses and reduction in voltage (Véronique Beillan et al., 2018).

[14] Device controlling the transformation ratio of the transformer to control voltage when load varies.

Elena Turienzo, & Carlos Madina, 2016). These plants should be smartly located on the grid in order to ensure an efficient control everywhere (RTE, 2004). However, in case they do not provide enough reactive power, other reactive power compensation means exist:

- Synchronous compensators, which are equipment providing a similar reactive power control as synchronous machines (see Frequency stability section)
- Other pieces of equipment such as capacitors, self-inductances, Static VAR Compensators (providing the same services as synchronous compensators but with a static, power electronics technology) and tap changers in transformers. These equipment are controlled by TSOs (and DSOs at the distribution grid level) (Brown et al., 2018; Véronique Beillan et al., 2018).

Static VAR Compensators, synchronous machines and compensators can provide a fast control, which cannot be provided by capacitors, self-inductances or tap changers. Hence the latter means are used in priority for slower control needs in order to keep enough fast control margin.

Synchronous machines (conventional power plants) and synchronous compensators provide voltage control services. They provide three different control mechanisms depending on the considered time horizon and geographical perimeter:

- Primary control is a local, automated and instant control. It regulates the voltage at terminals of alternators' stators.
- Secondary control is automated. It coordinates the actions of the alternators of a given region and regulates voltage at strategical points on the grid. This control acts at a one-minute time scale.
- Tertiary control is not automated. It coordinates voltages across regions and enables plants participating in the primary and secondary controls to keep control margins, by starting other plants or modifying the operating points of some plants.

At the distribution grid level, consumers have incentives to install capacitors to compensate for reactive power losses. These incentives might not be sufficient. Hence some passive voltage control equipment are installed on the distribution grid. They are automatically controlled by DSOs.

Voltage is regulated on the transmission grid in priority, and then on the distribution grid. Indeed, a stable transmission grid avoids system-wide voltage collapses. This is why voltage regulators act faster on the transmission grid than on the distribution grid.

C. Voltage control in power systems with high share of inverter based VRES: a near-term engineering challenge but a low priority consideration for long-term planning

Inverter connected RES can provide reactive power if the inverter is properly designed (IRENA, 2017) but this certainly affects their ability to provide active power (Kroposki et al., 2017). This inverter technology is already being offered by manufacturers (Brown et al., 2018; IRENA, 2017).

With such inverters, wind and PV generators have reactive power control capabilities, only as long as they produce power (BMZ Deutsche GIZ GmbH, 2013). However, for the same installed capacity inverter-connected plants can deliver lower levels of instant reactive power than SMs.

Batteries could also provide such services (IRENA, 2017).

But the integration of VRES can still have negative impact on voltage stability:

- Reactive power cannot be transferred over long distances but must be made available locally. However, especially wind farms are very often located in remote areas (remote from load centers). For this reason, even if wind farms are able to deliver reactive power, it may not be made available at the location where it is actually needed.

- The connection of generation plants to the distribution grid (also known as decentralized, or embedded generation, for example small scale RES) requires adaptations of the voltage control system (Heard, Brook, Wigley, & Bradshaw, 2017; IRENA, 2017). Indeed, voltage control has originally been designed for centralized power systems[15]. Hence if more power production is connected to distribution grid, transmission grid will have to adapt its control mechanisms (Véronique Beillan et al., 2018).

However, these issues can typically be mitigated at moderate costs by installing additional reactive power compensation where needed, either based on switched capacitor banks (mechanical switched capacitors / MSCs) or static var compensators (SVCs). These technologies are readily available. Such adjustments are not expected to significantly alter the long-term transition path. The required dynamic performance of the additional reactive power sources must be identified by dynamic simulations looking at near-term, local voltage stability aspects and transient stability aspects. (BMZ Deutsche GIZ GmbH, 2013; IRENA, 2017; Brown et al., 2018)

The impact of VRE generators on voltage control, therefore, may be assigned a low priority in planning long-term transition. The details of the voltage control design will be tackled on a near-term basis. The associated costs are likely to be low compared to power capacity costs (IRENA, 2017).

Some optimizations of the distribution grid might be possible too, such as a coordinated control of transformers, or local voltage control on the low-voltage transmission grid (ENEDIS, 2016).

Recommendations on voltage control

A scenario strategy about voltage stability should be defined and justified. It should include considerations on the decision to study voltage stability or not.

If the strategy is to discard this aspect, a qualitative analysis of the limitations it induces in the study should be performed.

The different aspects which are considered should be reported, and their links to the study strategy should be outlined.

Hereunder are aspects of voltage stability which may be reported about. These aspects are impacted by the overall structure of the PS. Questions in italic are examples to illustrate the aspects which are dealt with.

- Voltage control operating results
- Overall methodology to assess those results
- Impacts and induced costs if voltage control is inadequate

In more details, here are aspects which may be considered to properly answer the previous points:

- Evolution of the architecture of the voltage control system with regard to the evolution of the capacity mix (especially the share of power production connected to the distribution grid). *Does the architecture switches from a step-down concept to a new one?*
- Equipment participating in the voltage control, depending on the speed (primary / secondary + tertiary) of the control: evolution of the available technologies with regard to the technological storyline. *Are new voltage control technologies available?*
- Evolution of the stock of equipment, drivers of this evolution, potential associated costs. *How many MSCs, SVCs, synchronous compensators, batteries, VRES units are installed during the scenario? Are there markets or regulations fostering this evolution? What are the associated costs? How much material does it consume to produce them?*
- Voltage control mechanisms (if they are significantly different from the current ones), voltage control operating results and potential impacts of these results. *Does the resulting voltage control system manage to keep voltage stable for normal operation of the PS? During disturbances? What interactions with society and the economy if it does not?*

[15] Typical voltage control concepts are strictly based on a step-down concept, where step-down transformers regulate the voltage of the next lower voltage level, which means that reactive power balancing is only possible in the direction from higher to lower voltage levels (BMZ Deutsche GIZ GmbH, 2013)

IV. Rotor angle stability

A. What is rotor angle stability and why is it important?

Rotor angle stability is the state in which the power system (PS) is when all the alternators of plants run at the same electrical speed. This common speed is the *frequency* of the PS.

PS stability is possible thanks to an elastic link called "synchronizing torque" acting through electric variables and synchronizing the generators between them.

When the synchronizing torque is broken (for example in case of a long short-circuit event), generators can start running at different speeds. PS frequency has no meaning anymore. The electric wave at each point of the grid is the compound of waves of different frequencies: voltage and intensity beats appear, which produces unacceptable constraints on connected equipments: overintensities, overvoltages… The power system is not stable anymore. (RTE, 2004)

Two contingencies can lead to a rotor angle instability:

- An undamped oscillatory perturbation (oscillatory stability)
- A critical fault lasting for too long (transient stability) (BMZ Deutsche GIZ GmbH, 2013)

The grid is instable by nature. Hence SM are designed to maintain their own stability and the global PS stability, through the tuning of their controllers: these controllers ensure that oscillatory perturbations are damped and that the SM stays synchronized in case of a critical fault. Modeling and testing are performed before the commissioning of SMs (Véronique Beillan et al., 2018).

However, especially in the lower frequency domain, in which inter-area oscillations are relevant, it is not possible to fully attenuate power oscillations with the above described mitigation measures. Here, power oscillation dampers (PODs) can be applied on the transmission network, which modulate the voltage for improving system damping through the voltage dependence of loads. (BMZ Deutsche GIZ GmbH, 2013)

Going from a synchronous machines (SM) based power systems (PS) to an inverter-based PS has implications on rotor angle stability.

B. Managing oscillatory stability in PSs with a high share of VRES requires next-**generation "grid-forming" inverters**

The current PS, dominated by synchronous machines, can be represented by a set of masses (machines) linked by springs (the grid). When a perturbation comes, a mass can come to oscillate, which naturally leads the other masses to oscillate. The whole system can react and filter this perturbation as the controller of each plant is properly tuned. (Véronique Beillan et al., 2018)

Because oscillatory stability is a small disturbance phenomenon, it is a system property being independent from the type of disturbance. Hence, in the case that an undamped type of perturbation exists, even the smallest of them will get excited, leading to a loss of synchronism. (BMZ Deutsche GIZ GmbH, 2013)

If synchronous machines are replaced with power electronics converters, then these converters must be set to be robust to the perturbation as opposed to follow and reproduce it (such as current "grid-following inverters") (Kroposki et al., 2017).

Grid-forming inverters can be used in order for them to be robust to perturbation and to contribute themselves to the rotor angle stability. They are also called Virtual Synchronous Machines (VSM). (Kroposki et al., 2017; Véronique Beillan et al., 2018)

This next-generation, grid forming inverters will be able to operate in low-inertia grids without a stiff frequency (that is, with a very low amount of SM's); however, this requires to increase the inverter current rating, hence its cost (Brown et al., 2018), possibly up to very high costs (Véronique Beillan et al., 2018).

C. Managing transient stability in high VRES share PS: general and specific studies must be led

Transient stability describes the ability of a power system to maintain in synchronism following large disturbances, such as grid faults. Because of the nonlinear nature of power systems, transient stability depends not only on system properties but also on the type of disturbance. Because of the complexity of the problem, transient stability can only be analyzed by a series of time domain simulations using dynamic models of generators, governors and controllers.

Generally, the impact of wind and solar generators on transient stability can be positive or negative, depending on each specific situation (their location, local topography of the grid). The impact of VRES must be studied in each individual case. (BMZ Deutsche GIZ GmbH, 2013)

Studies must be led to estimate the potential impacts of a decreased inertia and short-circuit power on the transient stability with the increased share of inverter connected plants. (Véronique Beillan et al., 2018)

Recommendations to scenario producers on rotor angle stability

A scenario strategy about oscillatory stability and transient stability should be defined and justified. It should include considerations on the decision to include them in the scenario or not. This choice depends on the Planning Question and on the study overall strategy. The different aspects of rotor angle stability which are considered should be reported, and their link to the study strategy should be outlined.

The following aspects of rotor angle stability may be reported about:

- The technologies used to ensure rotor angle stability, their evolutions through the scenario (in terms of maturity and commercial availability, costs, efficiency…). If these evolutions are deemed uncertain, sensitivity analyses may be proposed.
- The equipment installed on the PS and the PS organization; the drivers of PS evolutions.
- For transient stability assessment, which requires very specific studies, simplified assessment methods, or modeling strategies may be proposed

V. Other ancillary services

A. Short circuit current

1. Short-circuit current: an image of the power sources in opposition to a fault

Short circuit current is the current which is measured in case of the worst short-circuit fault[16]. It is composed of the currents coming from the sources which are in opposition to the fault.

Different types of power sources contribute differently to fault opposition. A Synchronous Machine can oppose perturbations by injecting up to 6 times its current rating. Inverter-connected VRES can contribute between 1.1 to 1.6 times their current ratings, due to the physical characteristics of interrupters composing the inverter.

(Kroposki et al., 2017; Véronique Beillan et al., 2018)

2. Evolutions in short-circuit current can require evolutions of the fault detection system

Fault detection systems on the grid are based on local current monitoring. If current reaches a given threshold, then a fault is detected, triggering corrective action. Hence a lowering of short-circuit current could lead to potential missed fault detections, which could endanger people and equipment (Véronique Beillan et al., 2018). For scenarios based on inverter connected generators, a lower amount of short circuit current would be available, leading to such risks.

On the other hand, more connections at the distribution grid level may lead scenarios to propose stronger links between the distribution grid and the transmission grid, bringing more short circuit current from the transmission grid to the distribution grid. (Julia Merino et al., 2016)

Also, the connection per say of a power generator (through an inverter or not) to the distribution grid might disturb the fault detection system. The protection system is designed for centralized PS (on-way flows). Hence, for a power plant being connected at distribution grid level, detection devices which would be located at the upstream of the new connection may cause missed detections or false detections (Véronique Beillan et al., 2018).

Another impact of low short-circuit current levels is a difficulty in starting big industrial electrical motors, which consume 6 to 7 times more current when they are being started than when they run.

3. Possible evolutions: adding short circuit current sources, updating **fault sensors or making the fault detection system "smart"**

For scenarios with more VRES and / or generators connected at the distribution grid level, several technologies can be proposed to conserve the efficiency of the fault detection system in a PS with more VRES:

- Synchronous generators could be installed at relevant locations and bring the missing short-circuit current. However this solution may not be the most economical (Brown et al., 2018)
- Over-current detection could be replaced by differential protection and distance protection, both of which are established technologies (Brown et al., 2018)
- Over-current detection could be updated by adding a flow-direction detection capability (Véronique Beillan et al., 2018)
- The fault detection system could be made "smart" by allowing a communication between all the detection devices. However, this would induce extra costs, cybersecurity concerns and resilience issues. (Véronique Beillan et al., 2018)

[16] This fault is called three phase bolted fault and it consists in a short circuit for the three phases together, as if they were bolted together; this kind of faults leads to the maximum short circuit current values

- The architecture of the protection system could be re-designed and modified taking into account the new connections (and those available technologies). (Véronique Beillan et al., 2018)

Concerning a possible difficulty to start industrial motors (as they consume 6 to 7 times more current when they are being started than when they run), synchronous generators can solve the problem. Another solution would be to equip big motors with electronical speed variators to decrease the starting current, albeit at an extra cost. This would however decrease load inertia which is useful for frequency stability (as mentioned p10).

Recommendations to scenario producers on short circuit current

A scenario strategy about fault detection should be defined and justified. It should include considerations on the decision to study it or not. This strategy depends on the Planning Question and on the study overall strategy. The different aspects of fault detection which are considered should be reported, and their link to the study strategy should be outlined.

The following aspects may be reported about:

- Evolution of the fault detection system: installed technologies and/or new architecture of the fault detection system; drivers of this evolution.
- Smartization of the fault detection system, in line with technological storyline; associated costs and potential impacts on PS resilience (especially in case of a greater coupling with the IT system)
- Evolution of the fault detection system efficiency: new risks of false, or missed detections; impacts of these risks.

B. Fault ride-through capability

Fault-ride through (FRT) is the capability of electric generators to stay connected in short periods of lower electric network voltage (voltage dip) until the faulted element has been cleared from the transmission system. The fault-ride through capability mostly depends on the reactive power control (which determines the necessary time to clear a fault) (Julia Merino et al., 2016).

In the case that a substantial amount of wind or solar generators will be connected that do not have the FRT capability, a single line fault in the transmission grid (which is a frequently occurring event) can potentially lead to the disconnection of a large amount of generation and hence might increase the amount of generation that can be lost because of a single fault. In such a case, FCR would react to stabilize frequency. Hence capacity reserve would have to be designed with the amount of generation not equipped with FRT capability.

However, because FRT-capability is a standard feature of modern wind and PV-inverters, all wind and PV-generators in a system can easily be equipped with FRT-capability for ensuring frequency stability. (BMZ Deutsche GIZ GmbH, 2013)

Recommendations to scenario producers on fault ride-through

Scenario reports should define and justify their strategy about FRT capability. The strategy should include considerations on the decision to study this capability or not, in line with the Planning Question and study strategy. The different aspects of FRT capability which are studied should be reported and linked to the overall study strategy.

The following aspects may be reported about:

- Evolution of the capacity share which is equipped with the FRT capability, by generation technology
- The potential impacts of this evolution on system reliability, costs.

C. Black-start capability

1. Black start: the ability to restart the electricity system in the case of a total blackout

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

Typically system operators use hydroelectric plants (which can generate as soon as the sluice gate is opened), diesel generators or battery systems, which can then start a gas turbine, which can then start other power plants (for example). (Brown et al., 2018)

This ability to restart a grid is critical to overall system reliability. To accomplish this, the generation on the system needs to be able to both act as a voltage source and provide adequate power to start electrical equipment with high in-rush currents, such as transformers and motors. (Kroposki et al., 2017)

2. Black start capability: a near-term issue for high VRES mixes; still under research for very high shares of VRES

Storage devices as well as VRES could participate in black starting the PS in times when they can provide energy, because they do not need power to start (Brown et al., 2018). However, the amount of current they can provide, which is lower for inverter-based VRES than for conventional power plants, must be sufficient to restart the thermal power plant equipment. The required amount of current depends on the topology of the grid (Kroposki et al., 2017).

Battery storage systems have been shown to be able to black-start gas turbines (Brown et al., 2018).

In any case, conventional solutions can still be used (hydropower, diesel generators). However, as long as the amount of generation and load is not sufficient, PS stability is very weak. During this phase, the variability of VRES could trigger protection devices, leading to a failed restart. As mentioned above, fault detection system must be adapted to high shares of VRES.

For scenarios with an inverter-dominated PS, black start must include a beat leader giving the frequency on which all other power plants can "connect". Indeed, the usual frequency beat provided by regulated conventional power plant (synchronous machines) can become too weak to efficiently operate. This question is still under research. (Véronique Beillan et al., 2018)

Recommendations to scenario producers on black start capability

A scenario strategy about black start management should be defined and justified. It should include considerations on the decision to study it or not. This strategy depends on the Planning Question and on the study overall strategy. The different aspects of black starting which are considered should be reported, and their link to the study strategy should be outlined.

Here are some of the aspects which may be studied:

- Black starting ability: equipment participating in this service, potential associated costs, evolution of the ability in the scenario time frame, potential impacts of a longer black starting time
- Beat leader presence especially with very high shares of inverter connected generators: equipment ensuring it within the scenario time frame, potential associated costs

VI. Planning for market designs and regulations: a near-term challenge but a low priority for long-term planning

Markets or regulations explain the incentives of agents to provide electricity, all the ancillary services and future ancillary services.

For each scenario, depending on the specificities of their markets and regulations, the changes in their PS may require market design, or regulations, evolutions. New ancillary needs might appear and should be remunerated in order for economical agents to propose ancillary services fulfilling them.

For example, the integration of VRES in UK and Ireland led those countries to alter their reserve market design in order to add slow ramp up and ramp down products. They also added a product for Fast FCR, and Irish market remunerates inertia.

In Denmark, markets have been created for short-circuit power and for reactive power. (Véronique Beillan et al., 2018)

In scenarios with high shares of VRES, power and ancillary services markets will have key issues to tackle:

- They should coordinate together in order to find the right market design for each of them. Indeed many technologies will participate in several markets at the same time (for example, synchronous compensators could participate in voltage control, in short-circuit power and in inertia at the same time). They should also coordinate with markets for other energies interacting with electricity (for example the heat network could participate in flexibility services by replacing electricity demand at the right time).
- They should answer the question of their geographical scale (local / regional / European markets), and of the interactions between different scales.
- As ancillary services might be more distributed, and especially coming more from distribution grid (where most VRES are connected), the questions of the interaction between GRT and GRD, and of the responsibility to ensure reliability, should be addressed. (Véronique Beillan et al., 2018)

However, the way markets are organized can be changed in a matter of a few years, at low cost. The mere question of planning market designs is not a priority for long-term planning, compared to the planning of physical devices composing, and structure of, the PS ensuring its proper operation.

Considerations on markets are included in the different recommendation sections as aspects that some scenarios may want to describe.

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