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

Technical file #6

Information and recommendations for scenario producers

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

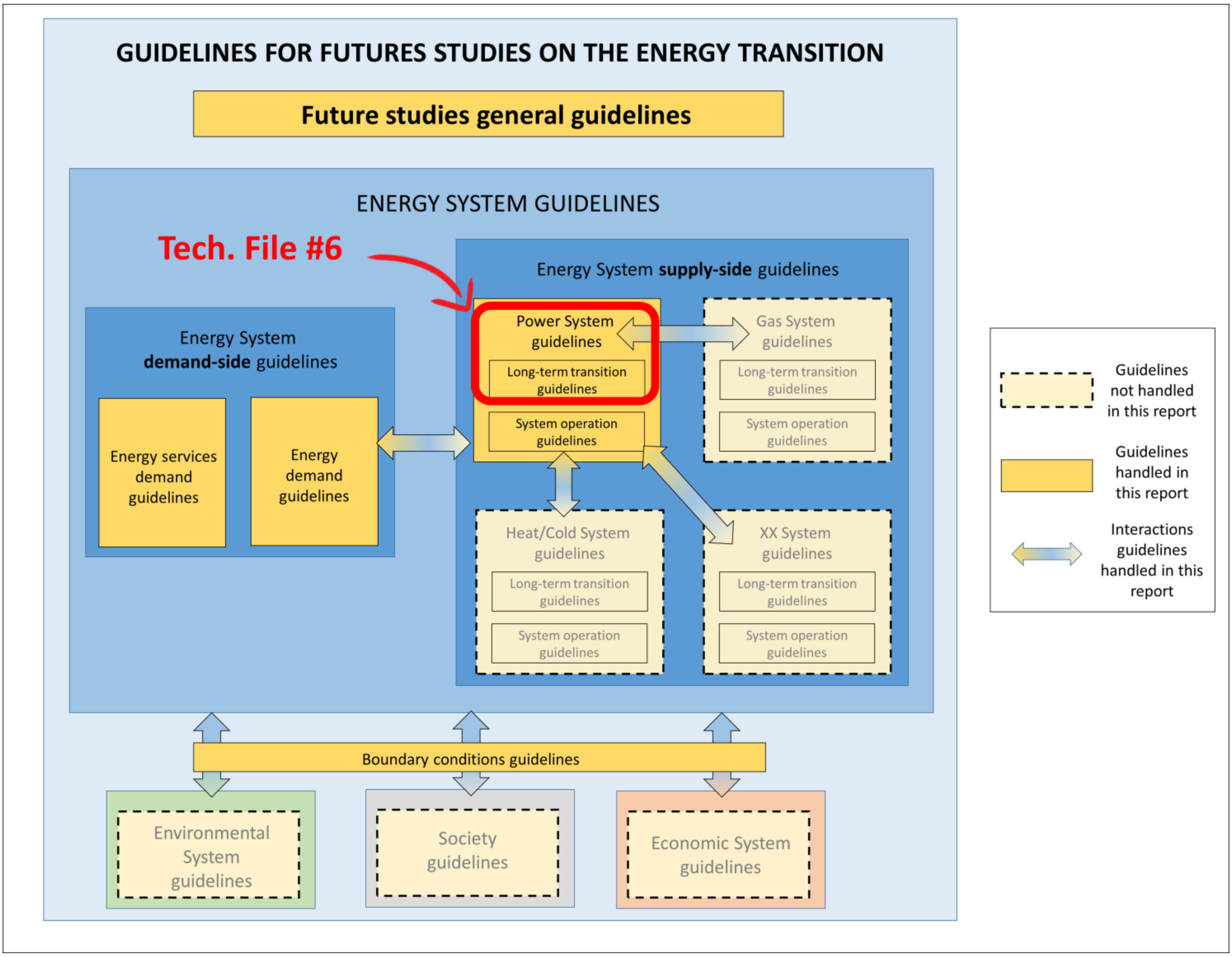
Our project, "Power Systems 2050 – Guidelines for future studies on energy and power transitions," started in January 2018, involved approximately 60 experts through interviews and workshops, reviewed more than 300 works, including about 20 future studies. The objectives and approach of this project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

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

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

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

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



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Reading keys

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

Recommendations to scenario producers:

These boxes contain the recommendations for scenario producers.

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

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

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

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

I. Describing the outline of the power system supply-side and its architecture

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

(EDF R&D, 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) and on economic conditions, this growth has been fluctuating (see boundary conditions section).

When speaking about electricity consumption, Watt-hours (Wh) are often used; for large, national PSs, TWh 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 such as steel production, and goods transportation.

Consumption permanently evolves, following a time pattern which is driven by our lifestyles[1]. Nowadays, the consumption shows the following pattern:

- 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.

[1] As developed in section about lifestyles, scenarios may propose changes in habits, or even in lifestyles, which in turn alter the consumption pattern. Scenarios may also propose technologies to alter demand without significantly altering lifestyles (demand-side management).

- 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.

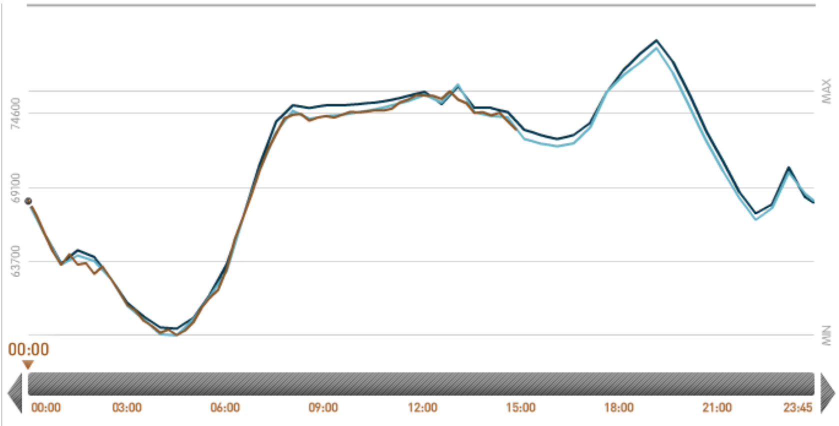

Figure 1: Source éCO2mix, RTE

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 form (Direct Current, DC) 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. It represents the instant power electricity can deliver and hence determines what kind of services can be provided by electricity (low power electricity cannot be used to generate heavy mechanical services such as powering a high-speed train).
- Energy is expressed in Watt-hour (Wh). It is equal to power x time. It represents how much energy has "flowed" to provide a given service.
- Frequency is expressed in Hertz (Hz). This value is useful only for alternative current. It represents 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 traditional power systems, the grid is structured in several layers in order to connect large production stations to end consumers. 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 and corresponds to high voltage levels. Large power plants, as well as industries requiring high instant power to operate 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 (small industries, households…). This is the "small road" network of electricity and corresponds to lower voltage levels. Smaller power plants (such as the majority of VRES plants) are connected to the distribution network.
- Trans-border 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[2].

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 busbars and disconnectors

[2] Capacity refers to an amount of available power within a PS. Emergency capacity refers to the production plants available to keep the PS operating after an unexpected event. Of course these plants must be connected to the grid in order to help the PS operating.

- Controlling and protecting the PS (control system, sensors, circuit-breakers)

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 (or vegetation), 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. Describing 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 (EDF R&D, 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).
  For example, 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.

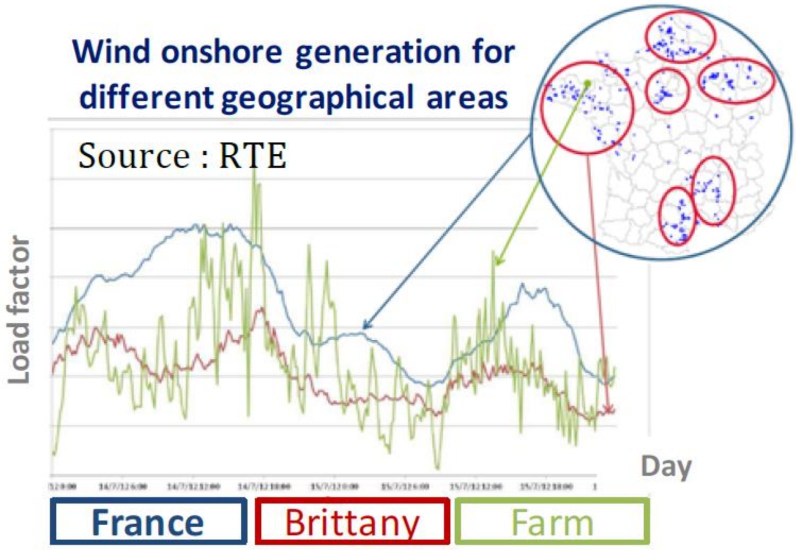

Figure 2: onshore wind generation for different geographical areas in France (EDF, 2015).

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 (EDF R&D, 2018; Foxon, 2013; France Stratégie, 2017).

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 crowdfunding; 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, 2017a) 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). Some aspects of the PS architecture are driven by individual decisions, the remaining aspects being driven nationally.

(ADEME, 2012) 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, for Carbon Capture and Storage (CCS) and 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, as was described above. 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, citizens' organizations, or prosumer citizens. 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[3] 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 (VRES or not) and electricity going one way to consumption spots. On the

[3] Flexibility refers to the ability of the PS to smoothly adapt to demand and unexpected events, as explained extensively in the section about operation.

contrary, it can be much decentralized with numerous small-scale generation plants (VRES 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… (see section about impact assessment and sections about surrounding systems)

II. Describing the evolution of the power system supply-side and its technological components

A. Concertely describing the drivers of the evolution of the PS supply-side

Scenarios use different approaches to model the evolution of the power system supply-side[4] over the scenario timeframe.

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

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.

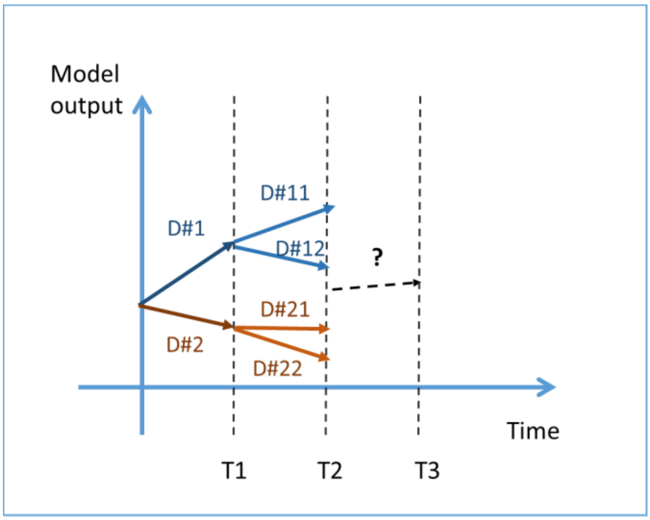

Figure 3: In the time-based approach, at each time step decisions are made by the model to drive the power supply-side system towards a direction. In this diagram, the possible decisions are represented by arrows and are numbered by D#xx. Of course, over the course of a simulation only one path is selected.

In the **intertemporal approach**, decisions are made about the power system supply-side 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 decision rules are applied over the whole trajectory within the time frame, as opposed to micro-

[4] See section about boundary conditions for a definition of supply-side, as opposed to demand-side.

decisions taken at each time step. Some models' documentations talk about "perfect foresight" of the deciding agents. The intertemporal aspect is more informative: 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 not understanding and concretely explaining why one decision was made at a given point in time in a scenario and not in another one.

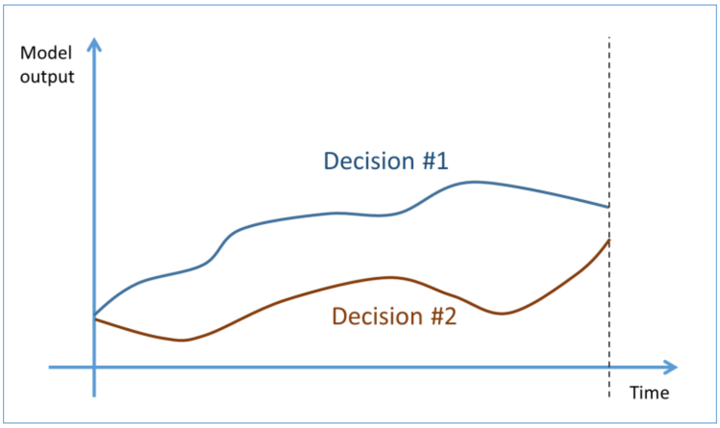

Figure 4: In the intertemporal approach, decisions are made by the model about whole trajectories, as opposed to decisions at each time step.

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 or without 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 applied 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[5] through electricity prices obtained over the trajectory to satisfy electricity producers. Prices affect the demand trajectory 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.

Levelized Cost of Electricity (LCOE)

Levelized Cost of Electricity is a cost indicator applying to a system delivering electricity, which measures the (monetary) cost involved in the delivery of electricity over a given timeframe.

The selected system can be narrow (e.g. a single power plant), or wider (such as the power plant and its connection to the grid, or a set of plants connected together through a transmission grid, or the whole power system supply-side), as long as it delivers electricity. This indicator does not apply to a system providing energy services, hence it cannot be applied to the whole power system.

LCOE is computed by dividing the costs associated with the delivery by the total amount of delivered electricity over a given amount of time (such as the life duration, or another characteristic time of the considered system).

In future studies, LCOEs are mainly used to simulate investors' decisions for electricity production project. As they measure a cost incurred by investors on a project leading to returns over several years, a discount rate is used to ensure a sufficient yield for them. The discount rate is thus very similar to the interest rate expected by financers.

By comparing the LCOE to the expected prices of electricity on markets, investors can decide to invest or not in the project: if expected prices are higher than LCOE, then the project is expected to generate sufficient return on investment for the investors.

For more details, see separate note on LCOE.

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 may be 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. Indeed, 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 ancillary 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 (see section on power system operation). 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

[5] Also see the consumption section.

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 (Loulou, 2016).

Such studies depict 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 (see box on LCOE above). 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 also models[6] 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, 2017a).

To simulate private actors' investment decisions, a private discount rate (WACC) can be used.

Weighted Average Cost of Capital (WACC)

WACC stands for "Weighted Average Cost of Capital". It is a rate allowing to integrate the remuneration expected by financers in calculations for a specific project. In other words, it is a discount rate used to include the cost of capital in the evaluation of the profitability of a project. This is why it is sometimes called "capital cost" (whenever a "capital cost" is expressed in %, it is a WACC).

More precisely, a project is considered profitable when its "net present value" (i.e., the sum of all expenditures and revenues, discounted with a WACC) is positive. This means **the same project can be profitable or not depending on the WACC value**. Therefore the WACC has a significant impact on the profitability of a project. This is particularly true for capital-intensive investments (i.e. projects with high CAPEX and low OPEX) which is precisely the case for VRES and nuclear. Therefore, decarbonized technologies viability is very sensitive to the WACC value. Fossil fuels are much less impacted since they are characterized by low CAPEX and high OPEX. Low WACCs will favor decarbonized technologies. It is therefore a **key element of the energy transition** given our present financing system.

Here is an example to give an idea of how sensible the WACC parameter can be: the LCOE (see LCOE section) of a decarbonized electricity generation unit can double depending on whether the WACC is 0% or 8%. Thus, at 8%, this means that half of the total costs is the cost of capital (these calculations were made for illustrative purpose, for a nuclear power plant with typical characteristics). In the LCOE calculations, this is due to the fact that increasing the WACC does not affect the CAPEX (in the numerator) while it decreases the value of other elements of the ratio.

This enables to understand why **WACC choices can have a significant impact on the trajectory of some scenarios**.

The value of the private discount rate, and therefore the value of the WACC, depends on a combination of risks. These risks are related to the country where the project takes place (country risk), its policy (subsidies, risk reduction mechanisms for the financers, etc.), the maturity of the sector and its acceptability (delivery and legal risks). In the case of the WACC, which is a project-specific indicator, its value also depends on the financing structure of the given project (debt-to-equity ratio, corporate finance or project financing structure, etc.)

[6] Entrepreneurs target the electricity production market and the capacity market.

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[7]. For each block and each year, if generation capacity is missing, technologies compete on cost considerations to fill the lack, through a technology portfolio selection process[8]. 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[9] 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[10] (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[11] 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. In all these case, preference rules are applied, each corresponding the preferences of the imagined dominant actors.

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

[8] 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.

[9] 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.

[10] They call this indicator the VALCOE, for Value Adjusted Levelized Cost of Electricity.

[11] 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%."

As another example, 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:

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 (see section on impact assessment).
- Method used to translate LCOE hypotheses into decisions
- When private discount rates (WACCs) are used, the chosen values and their evolution should be explained and justified. *Which factors influence these values? What about regulations and the market structure? Is the State setting up a support mechanism for a specific sector? If a sector becomes more mature during the scenario, to what extent can its discount rate be reduced?*
- 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 power system components participating in the portfolio selection process (inventory): *are parts of the grid participating?*
- 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, explaining the different decisions driving this evolution.

B. Transparently describing the technical and economic characteristics of PS supply-side components 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.

We describe in this section the different characteristics of PS supply-side technologies which usually drive the PS evolution, or which are usually used to describe its evolution. The different considered technologies are in the following categories: production plants, storage technologies, grid components. We describe characteristics linked to the operation of the different technologies within the PS supply-side and to their interactions with surrounding systems (that is, their economic impacts, environmental impacts, and social impacts).

These characteristics are first order drivers of the scenarios' results, would it be in terms of PS evolution or in terms of its impacts on surrounding systems. As previously described, different rules are used to drive the PS supply-side evolution. Depending on these rules, a few characteristics may largely drive this evolution. For instance, cost hypotheses are first order drivers of the results of studies using a cost-optimization rule.

From one study to another the characteristics of technologies may vary, for the following reasons:

- For the same technology, the nature of input characteristics (exogenous data) used to drive the mix are not always the same. Thus, two different studies may use different characteristics for the same technology. For example, one study may take into account capital expenditure indicators of power plants to determine the mix whereas another could use purely technical characteristics (energy conversion efficiency, ancillary services…).
- The data sources and assumptions used are numerous. Thus, two different studies may use different values for the same characteristic of 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.

Recommendations to scenario producers are provided after describing the nature of the characteristics of technologies relevant for future studies on PS supply-side. A few specific, extra recommendations are provided for some characteristics.

1. Concretely explaining the evolution of the characteristics of PS supply-side technologies

Most of the characteristics of PS supply-side components 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. In future studies, technical progress often appears in cost characteristics.

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 rates 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.

Many studies rely on experts from academy and from industry as well as on reports from various institutions working on the energy sector to build their assumptions about the characteristics of the supply-side technologies and their evolutions through the scenario timeframe, such as (ADEME, 2012; ADEME, 2015; ADEME / Artelys, 2018).

As a conclusion, the evolution of the characteristics of technologies may be defined as boundary conditions (that is, exogenously) or may be modeled (that is, determined endogenously).

In any case, in future studies the evolution of the characteristics of technologies is not justified by narrative elements. They are justified by references to other studies, or to the experts who have been consulted for producing them. Hence **the evolution of technologies is not explained in a concrete way** from the point of view of the industry, or of State and corporate research. The relations between technological progress and research funding, industrial development, industrial innovation, labor cost linked with industry offshoring, price of fuels and materials are blind spots for future studies.

2. Technical characteristics for production units

In this section, we consider the different technical characteristics of production 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	Maximum installation rate	Production profile	Load factor	Availability factor	System storage function	Ancillary services	Impact from climate change
Wind															
PV															
Nuclear															
Gas															
...															

Figure 5: Production units' technical characteristics table

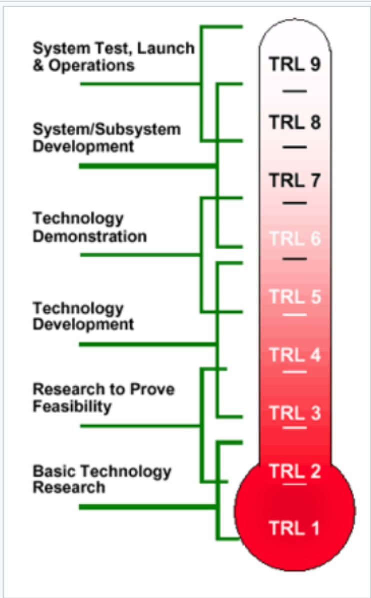
a. Technology maturity : a combination of TRL and CRI indicators

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.* »

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.



NASA Technology Readiness Levels

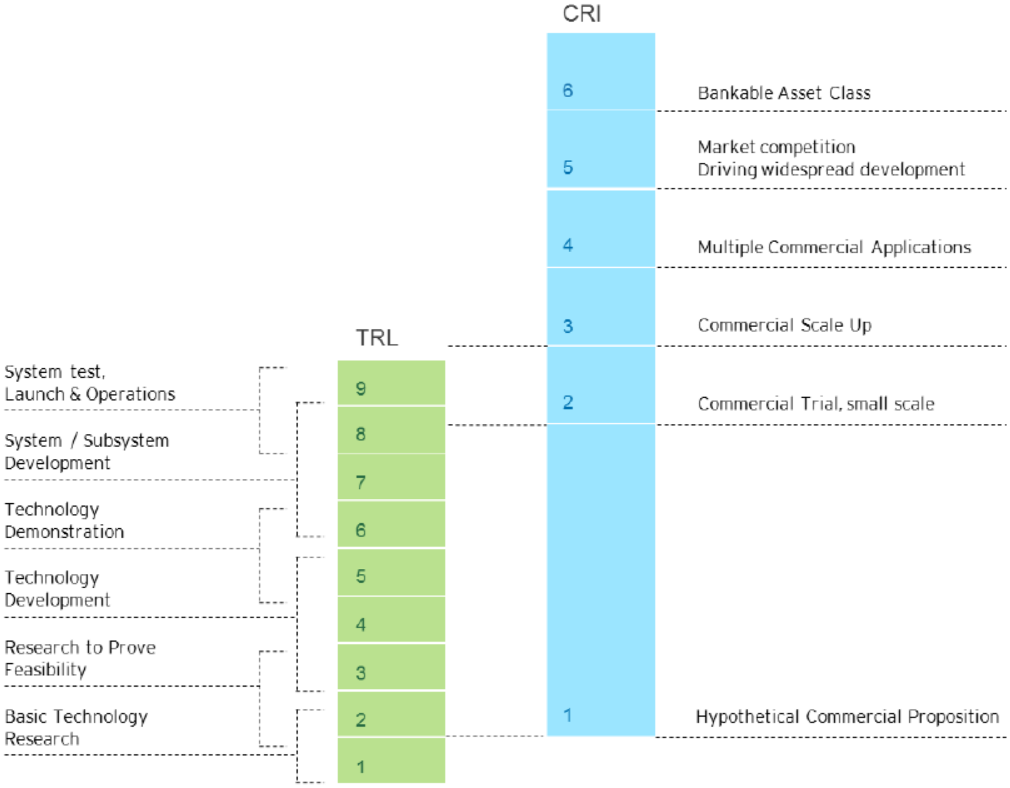
Source: Wikipedia

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.

b. Unit capacity

Unit capacity is the production capacity of a single installed unit. The definition of what is considered as a "unit" may vary between studies. The unit capacity can be expressed in Watts (kW, MW, GW) but also in W/m², or W/any relevant functional unit, depending on the unit definition.

Units may be simplified in scenarios as continuous capacities. For example, number of solar panels (discrete values), as opposed to square meters of solar power (continuous values) may be considered; number of coal power plants (discrete values), as opposed to an installed capacity of coal power, may be considered.

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.

Recommendations to scenario producers

Scenario producers should consider the following aspects about unit capacity:

- Precise definition of a unit, and physical units to describe this evolution
- the evolution of 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?*
- discrete or continuous description of installed capacity. *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"?*

c. 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.

d. Life duration

This is a useful parameter to understand the **power production mix evolution pace**. Its definition may not be provided by, or may vary across, future studies. 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).

Recommendations to scenario producers

Scenario producers should specify the definition of this indicator: *is it a "technical" lifetime or an "economic" lifetime which is considered? Something else? What definition is used?*

e. 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.

However, these terms may correspond to simplified visions of production technologies and as such may be bound to remain ill-defined.

Indeed, as explained in the section about power system operation, it may happen that some 'variable' technologies can be controlled to a certain extent, typically downwards. Moreover, dispatchability can be disaggregated into several characteristics depending on the forecast horizon which is considered: e.g. ramp up and ramp down capabilities, current operating point compared to minimal or maximal operating points etc. (see Power system operation file for more insights on this topic).

Recommendations to scenario producers

Scenario producers should consider the following aspects about dispatchability:

- Considerations on the degree of dispatchability of the technology with regards to different forecast horizons (see section on PS operation)
- Considerations on the direction of the dispatchability: dispatchable upwards and/or downwards.

f. 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. For instance, biodiversity conservation regulations may apply for hydropower plants, requiring them to release a minimal amount of water flow.
- 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.

g. Resource predictability

Another important element with regard to dispatchability is the **ability to predict plant production**. This particularly applies on VRES and depends on how the resource is stable within a day and over the year, and also on the evolution of knowledge and modelling capabilities on this particular resource. The flow or stock nature of the resource is key in predictability[12].

[12] Stocks are much more predictable even though unexpected events in the logistic chain are possible.

h. 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). For solar irradiation, variations in theoretical potential are negligible 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. Sustainable potential may evolve depending on different desirability issues (see section on desirability).

These potentials can be computed for different instant power levels (as opposed to average power over the year). Energy services require minimal amounts of instant power to be provided, hence it may be useful to assess the potentials in terms of instant power. For example, some industrial processes require high instant power. Such power cannot be provided by some technologies.

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)

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.

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)[13], 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.

Recommendations to scenario producers

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).

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

i. Maximal installation rate

In the real world, there are obviously different types of **limits** to the installation pace of different units. In scenarios, those limits depend on the hypotheses made in the storyline and therefore they may vary from one scenario to another.

This can be linked to resource potential, as resource quality can decrease when the best locations are already covered by new installations.

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).

Recommendations to scenario producers

Scenario producers should substantiate the observed installation rates in their scenarios, with regards to economic context and workforce context (skill management, education system, human resources management).

j. Production profile

Production profile is the **hourly production potential** of a production unit. For a renewable variable unit, 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. The previously mentioned decrease in renewable resource quality as best locations are progressively used appears in the production profiles of new sites.

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.

k. Load factor

Load factor expresses the amount of energy produced over a time period as compared to the maximum theoretical amount of energy it could have produced in optimal conditions. This parameter can be expressed as a percentage of this maximum or as the equivalent number of maximum production hours per year.

Future studies generally assume the load factor of VRES as a boundary condition for the long-term planning of the PS. Load factor 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.

Load factor for dispatchable production technologies is not used for the long-term planning of the PS (this indicator is less informative for dispatchable production) but can be an output of the hour-by-hour simulations. The obtained load factors depends on the role within the PS the technology has (base load / mid-merit / peak load / flexibility back-up…)

l. 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 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 during peak load periods.

m. System storage function

Some production technologies may have an **additional storage function** besides their production function. Two types of storage can be distinguished: 'system' storage or 'local' storage:

- A ***system storage function*** allows to store electricity from other production units and as such provides a storage function 'from the power system point of view'. This is the case for the great majority of storage systems.
- A ***local storage function*** only stores energy from the associated 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, local storage function can instead be considered as related to dispatchability.

For instance, in the case of hydropower, it may be interesting to distinguish hydropower alone (no system storage function) from mixed pumped storage hydropower (PSH) (both system production and storage function) and from pure pumped storage hydropower (storage function only). Indeed, resource constraints are different for mix PHS and pure PHS.

n. 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.

o. Impacts from climate change

Climate change we are experiencing has and will have increasing impacts which can affect production 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**. These impacts depend on the geographical perimeter of the future study and on the storyline about climate change level.

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).

3. 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).

In our framework, storage is included in the PS supply-side, even "behind the meter storage". Indeed, we define the demand-side system as the set of appliance and energy consuming devices which provide an energy-service to an end-consumer, that is, those equipment which transform final energy into useful energy. This excludes all forms of energy storage.

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 (as in homes, hospitals, industrial sites etc.) or mobile (as in electric vehicles).

Storage duration

This is the characteristic time of the use of a storage unit. Some storage systems are more cost efficient for short-term storage while other are more cost efficient for long-term storage. Several types of key periods can be distinguished when it comes to storage needs generated by high shares of VRES: 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 during which the storage can release energy. This is another key characteristic as maximum power determines the services the storage can bring to the PS, such as how much it can contribute to reserves or to black start capability.

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), in which case life duration is not a relevant indicator to express storage system durability.

For some storage facility, such as for flywheel energy storage, duration of use may be more relevant.

Efficiency

This is the ratio between energy output and energy input. It enables to estimate how much energy is lost when it requires to be stored.

Reaction time

Reaction time indicate how fast the storage system can release, or stop releasing energy when needed (ENEA Consulting, 2012). Ramp up and ramp down dynamics can also be used for a more precise description of reaction time. If reaction time is short enough, the storage unit can provide some ancillary services, or reserve capacity to the PS supply-side.

Storage potential

The storage potential can be estimated quantitatively or qualitatively by identifying the main limits to the development of this type of storage. Storage potential is analogous to the resource potential for production units. For example, (ECF, 2010) 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 production 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.

Recommendations to scenario producers

Other technical characteristics for storage units can be covered and discussed in scenario reports.

For example 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 could be provided.

4. 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 such as worker wages and regular maintenance operations and variable costs such as the purchase of fuel and quotas on carbon market for some production 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 note on LCOE for more details.

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 cost 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 box on WACC above 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 and structures, a dense and stable industrial fabric to avoid bottlenecks. See section on employment assessment for more details.

5. 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

The corresponding interactions with the environment are explored more in detail in the section about Environmental assessment.

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 at world scale 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 hazardous and nuclear solid 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.

Recommendations to scenario producers

Other environmental characteristics can be covered and discussed in scenario reports. 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 Life Cycle Analysis 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.

6. 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

Impacts on human ecology relates to impacts such as wind turbines generating noise or shadows, or possible smells from biogas infrastructure, impacts of installing a dam such as possible population displacements but also possible new recreational areas or irrigation support, etc.

7. Recommendations to scenario producers

Recommendations to scenario producers

Scenario producers should provide information for each proposed characteristic, for each supply-side technology they include in their study.

Considerations on the choice to include such or such technology should be provided and justified (e.g. for example, for a lack of maturity based on a maturity indicator, for robustness of the study…). *Why this list of technologies? Have any technologies been deliberately exclued? Is a TRL or CRI criterion used?*

Considerations on the **level of granularity** of the description of technologies (one or two types of wind power or PV, two or three types of hydropower, etc.) should be provided.

For each proposed characteristic applicable to the technology, considerations on the choice to take into account this characteristic in the study should be provided and justified with regards to the study strategy (selected impacts that are studied, etc., see section on future studies).

For those characteristics which are taken into account, the following aspects should be considered:

- Nature of the characteristic: if necessary, a precise definition of the characteristic may be provided
- Value and evolution of the characteristic within the scenario timeframe. Units used should be specified as it can change from one technology to another. Also, if the variable is an aggregate (e.g., "OPEX"), what it contains may be explained.
- Determinants of this evolution.
    - If the evolution is an exogenous variable or parameter, its source should be presented (workshop, literature, discussion with industry stakeholders, academics, other expert opinions, etc.).
    - If it is endogenous, its determinants within the model should be described.
- Role, and importance in the evolution of the PS supply-side mix: is this characteristic taken into account to drive the supply-side evolution? How? Is it a first order driver of the results?
- Sensitivity analysis: is the characteristic a first order driver of the results AND uncertain? Has a sensitivity analysis been performed with this characteristic?
- Considerations on transparency: reasons should be provided for not publishing the values associated with a characteristic which is used in the study. For example "confidential data", "commercial data"…
- For some characteristics, qualitative considerations only may be provided if relevant, such as for some environmental aspects (see corresponding annex).

In order to gather all the information about supply-side technologies, scenario producers may fill in the proposed tables with relevant substantiation depending on the characteristic and the study report organization (values, curves, qualitative considerations, references to a paragraph of the report which already handles the question, etc). Parts of the tables which do not evolve across scenarios may be presented once for the entire study, whereas those characteristics which evolve between scenarios may be presented for each scenario.

These tables are intended to be flexible. For example, if some technologies are described with a high granularity, they may be different only along a few characteristics (for example, two types of wind turbines may only differ by their average load factor and CAPEX). In this case, the associated columns may be split to describe these differences. If characteristics which are not considered in this framework are deemed important by scenario producers, columns may be added.

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.

Here is a short example for a fictional study:

	TRL	Unitary capacity	Efficiency of new plants	Life duration (years)	Load factor	...
PV	Not used	See paragraph 2.1	Not used. See p105	25	Confidential data	
Wind		See paragraph 2.2		30 Repowering has been considered (see p44)		
Hydro		See paragraph 2.3		50		
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 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.

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

C. Transparently describing grid evolutions and its impacts

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

The transmission grid is rarely finely modeled. Some studies model 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, 2017a) in order to get precise information about where and how the grid should evolve.

Distribution networks are not represented in national, supra-national or world long-term models, certainly due to their high complexity and high amount of data required to model them. As explained in the section about operation of the PS, VRES are mostly installed on the distribution network so far, which may require significant adaptations for that matter on its structure and/or its operation, depending on the scenarios. The consequences of such adaptations are blind spots of current future studies are they do not describe the materiality and the spatial organization of this network.

For example, for scenarios assuming high local production, storage and consumption through the distribution network, the control of this network needs to be adapted in order to operate as a collection and dispatch network, enabling energy to flow in both directions in power lines (see section on PS operation for more details).

Considering grid spatial architecture is also important if the power system physical architecture significantly evolves (for example from highly centralized to decentralized).

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, or consumption locations), the various impacts of these changes should be estimated using a tool which represents finely enough (in spatial terms and in temporal terms, depending on the tested impact, as explained in the section about PS operation) 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 interconnected PSs.

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 interconnections which are implemented in scenarios should be achieved. The following aspects should be considered:

- Type of power transmission (AC or DC)
- Type of line which is used (overhead, underground, subsea)
- The economic, environmental and social characteristics of interconnections: the corresponding technology tables should be filled.

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

3. Smart grid equipment

Smart grid technologies are much talked about, including in "informative sections" of future studies reports. They are often described as Information and Communication Technologies (ICT) which would enable to conveniently integrate more VRES in the PS without decreasing its reliability, that is, at a lower cost (European Commission, 2011; Greenpeace, 2015; World Energy Council, 2016). However, no concrete description of what these technologies are or how they would function is provided. In that sense, future studies within our scope do not implement smart grid technologies techniques in their scenarios.

More concretely, (RTE, 2017b) considers three main functions for smart grid technologies, as based on already mature technologies: storage, active management of demand in the industry and in dwellings, VRES curtailment. Other functions, like automated fault detection and dynamic estimates of flow capacity in power lines, are already being implemented in the French grid.

These functions (storage, demand side management and VRES curtailment) are much involved in scenarios with high shares of VRES. Storage has already been discussed above, and the services it can provide are discussed in the section about PS operation. VRES curtailment has already been discussed in the section about PS operation too.

a. Demand-side management for dwellings

Power demand can be generated by different kinds of energy services. Some of these services can easily be shifted in time: water heating thanks to the thermal inertia of hot water tanks, space heating thanks to the thermal inertia of dwellings, charge of electric vehicles due to the storage function in the car and the fact that cars are not always in use.

However, different households may have different practices. These practices may induce desirability issues if they are modified during a transition (see section on desirability). In any case, demand shifts imply a loss of utility for consumers, hence some form of incentive should be implemented for demand-side management to be accepted by households (communication, price incentives, bans or obligations, see section on behaviors and lifestyles…).

Demand-side management for dwellings can be performed by smart meters, or by dedicated boxes able to actuate the equipment and to communicate with a planning entity (aggregator, markets, etc.).

b. Demand-side management for industries

Industries may accept to shift their power demand under some forms of incentives. Different types of industries may accept such shifts at different costs, depending on how "easy" the shifts are (that is, how much added value is lost because of the shift).

For example, some industries may accept short time shifts due to some forms of inertia in their processes, such as cold production for the food industry, supermarkets, or heat production…

Recommendations to scenario producers

Scenario producers should be transparent about the smart grid technologies and techniques which are implemented in their scenarios. The following aspects should be considered:

- Smart grid functions: the concrete functions provided by the proposed technologies should be described
- Technology maturity: the maturity level of the considered technologies as well as narrative elements to justify its evolution during the scenario timeframe should be provided
- The economic, environmental and social characteristics of smart grid technologies: the corresponding technology tables should be filled. See (RTE, 2017b) for details and guidance.

Specifically, for demand-side management techniques, the following aspects should be considered:

- Type of uses, and actors which are impacted
- Specific technologies which are used to enable the management

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

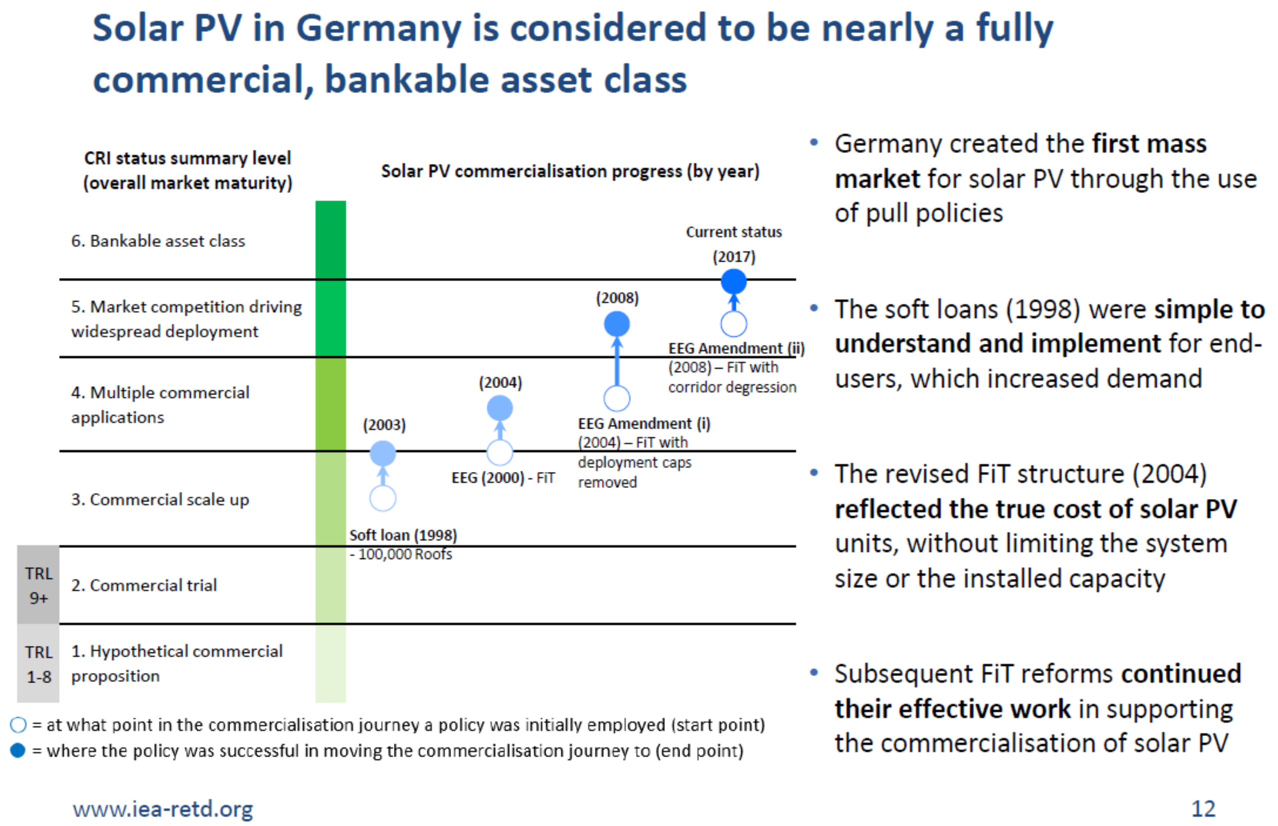
- Transmission lines table

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]

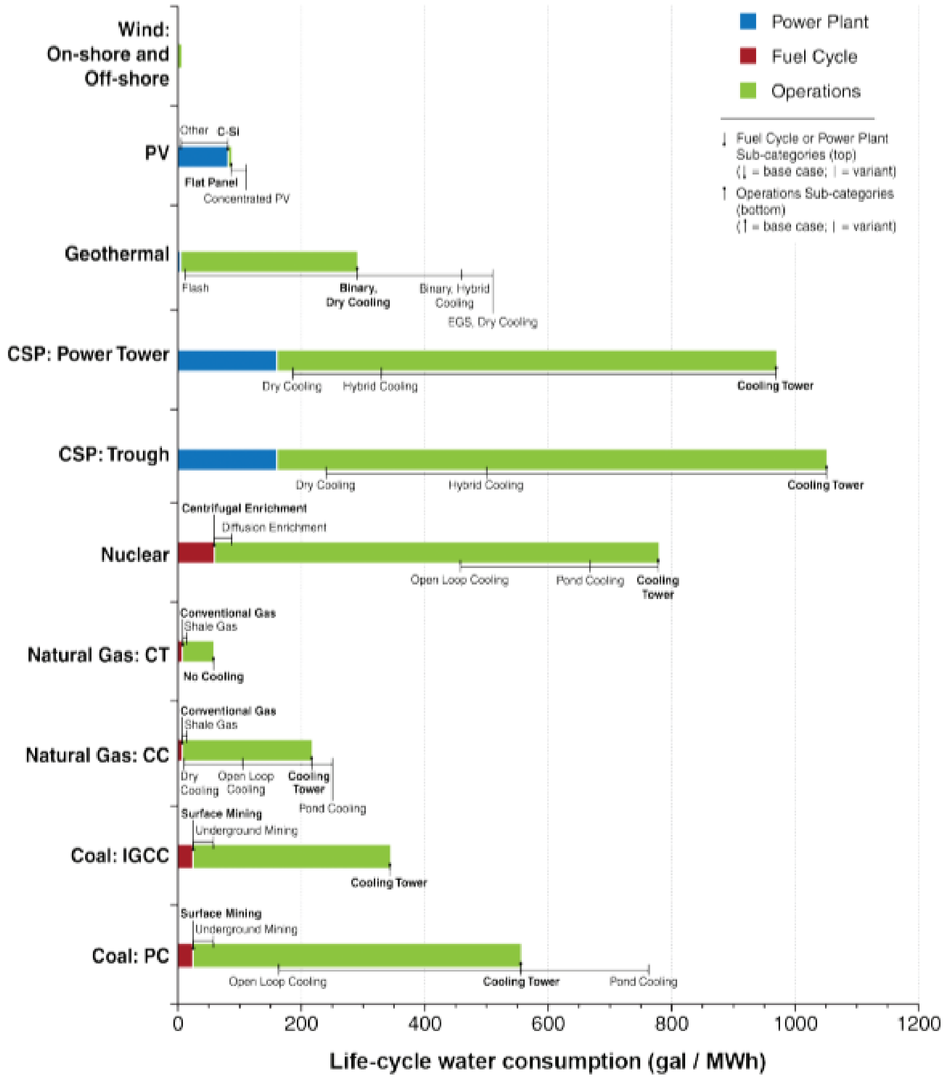
Materials (ton/TWh)	Generator only				Upstream energy collection plus generator			
	Coal	NGCC	Nuclear PWR	Biomass	Hydro	Wind	Solar PV (silicon)	Geothermal HT binary
Aluminum	3	1	0	6	0	35	680	100
Cement	0	0	0	0	0	0	3,700	750
Concrete	870	400	760	760	14,000	8,000	350	1,100
Copper	1	0	3	0	1	23	850	2
Glass	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)

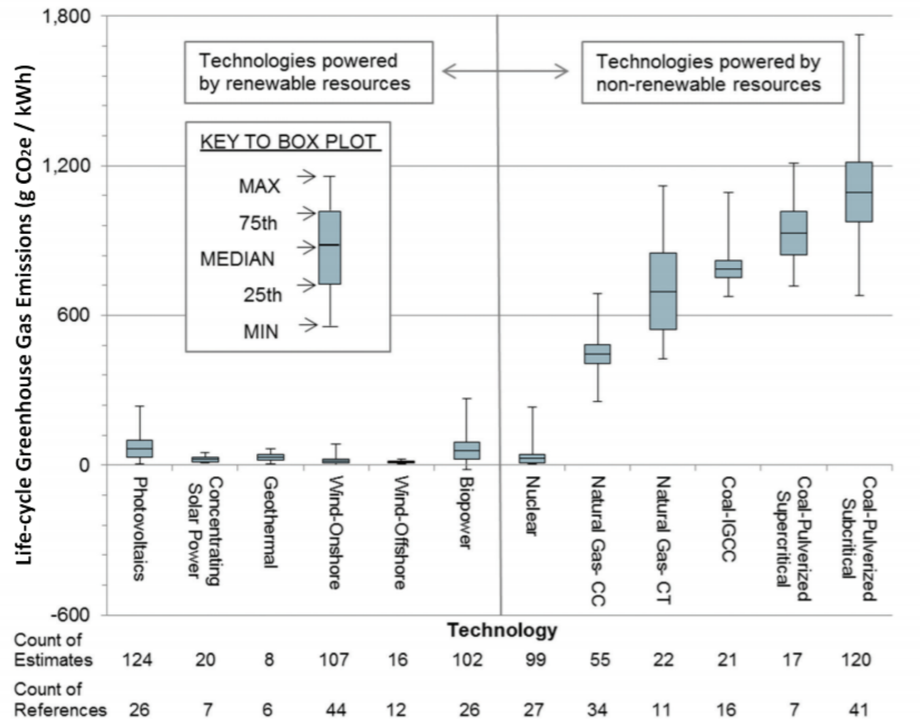
Energy technology	m^2/MW	System boundary Power plant site only; does not consider energy resource mining or collection, processing, or transport area, or land used for waste disposal
Biomass: direct-fired	9,000–45,000	Power plant site only
Coal	270–8,000	Power plant site only
Coal: CCS	12,000	Power plant 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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