Power system operation in energy transition scenarios

Technical file #7

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.

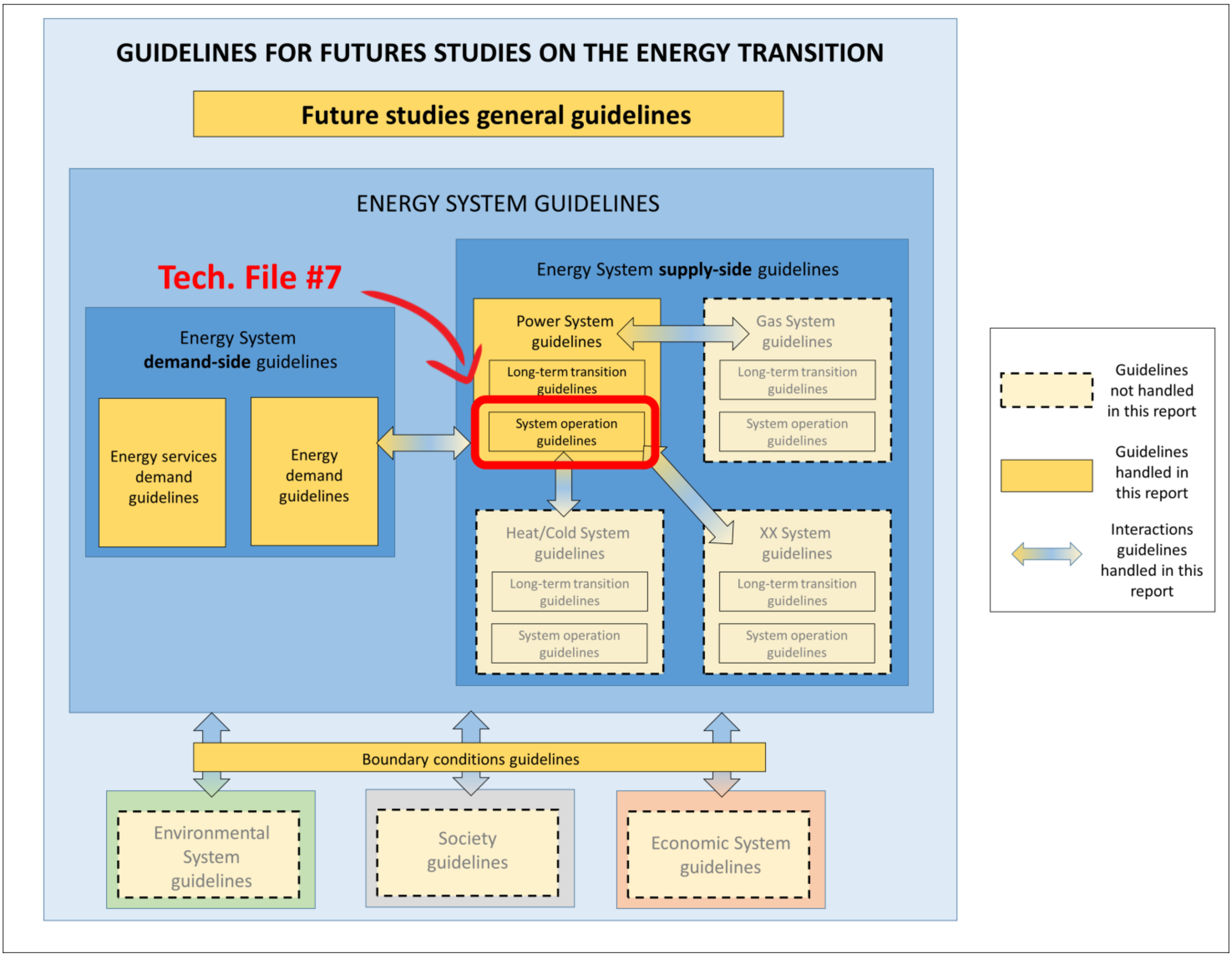
Our project, "Power Systems 2050 – Guidelines for future studies on energy and power transitions," started in January 2018, involved approximately 60 experts through interviews and workshops, reviewed more than 300 works, including about 20 future studies. The objectives and approach of this project 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 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. Taking into account system reliability in future studies: a key task which is more difficult for scenarios with larger shares of variable renewables

A. Reliability is the probability a power system operates well on the long run

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

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

In Europe, countries have different ways to measure reliability, either through probabilistic assessment (in %) or through a deterministic one (yes or no). For example, in France, Belgium and the UK, a 3 hour/annum standard is set (corresponding to a 99.97% reliability). In other words, the objective is that no failure happens (nobody is cut from power) during the whole year, except for three hours at maximum[2]. In Sweden and Spain, an indicator representing the amount of available security margin (called capacity margin) must be over a threshold.

The reliability criterion is key: models used by power system planners show that the reliability requirement significantly constrains the possible power systems. In addition, the higher this requirement, the higher the total system cost.

However, compliance to this criterion is difficult to assess in future studies when it is defined as a probabilistic criterion. Indeed, several situations would have to be tested for each state of the power system during the transition[3], in order to conclude that each of these states are reliable enough. Some argue that future studies handle so much uncertainty because of their far ahead time horizon that it is pointless to test many different situations of what would appear as second order uncertainties; instead, reliability criteria such as large enough amounts of magnetic energy reserve and kinetic energy reserve could be used as necessary conditions (Drouineau, 2011). Some studies test several different years and check how often each state of the power system fails. The selected years differ in their weather patterns, which is assumed to represent most of the uncertainty power systems with high shares of Variable Renewable Energy Sources (VRES) will undergo.

B. The threats on power systems and the levers to ensure their reliabilities

PS malfunction can be caused by:

- Consumption or production variation
- Weather events (thunder, gale, frost, flood, hot or cold weather,…)

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

[2] In France, the criteria is being detailed (2019): a failure is defined as the use of "post-market" mechanisms due to imbalances between power demand and supply. Failures are accepted up to 3hr/yr. A new criterion for power outage is set: power outages must not happen more than 2hr/yr in average (RTE, 2019).

[3] In future studies, the power system is represented as a snapshot every year, or every five years, until time horizon is reached.

- Technical failures or aggression from outside
- Human mistakes in the operation or maintenance of the system

(RTE, 2004)

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

These events can lead to disturb some key electric parameters which must remain stable: frequency, voltage, and rotor angle. Hence the power system must be designed so as to display the following qualities:

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

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

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

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

The protection system supporting the PS and acting as its sensory and actuation organ for detecting faults[4] and correct them must correctly operate for the PS to react fast enough to fix or isolate faults. Currently, generation units must provide **enough fault current** and be equipped with **fault ride through capability** for the protection system to operate correctly.

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

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

A good overview of the concept of power system reliability and the different means which can be proposed to ensure it during a power system transition is provided by (Boston, 2013).

Recommendations to scenario producers

A study strategy about system reliability should be made explicit. It should be substantiated with regards to the driving questions. The following aspects should be considered:

- Level of reliability. The considered reliability indicators as well as their minimal levels should be provided. These choices should be justified. In case reliability decreases from today's levels, considerations on desirability issues should be included (see section on desirability).
- Method to assess reliability, including considerations on the probabilistic nature of the selected criterion. Methodological guidance can be found in (Drouineau, 2011; Krakowski, 2016). *How many years, or*

[4] Faults are short-circuits and insulation faults

situations, are tested for each state of the power system? What parameters change between the tested years or situations? How do these tests enable to conclude on the reliability level?

- Key electric parameters and ancillary services which are taken into account in the study. The corresponding list should be provided and justified.

In this technical file we provide information on the different aspects of reliability to highlight which of them must be considered, and in which type of scenarios they must, in order to **properly integrate the physics of power systems in future studies**. A fundamental characteristic of these aspects is the large range of time scales they cover (from the millisecond to the year), implying great difficulties to model them in future studies. Similarly, these aspects cover a large range of geographical scales (from the local scale of a power grid segment to the national scale of the whole power system) (Krakowski, 2016).

However, these constraints must be taken into account to propose scenarios in line with the laws of physics. For scenarios **with larger shares of variable renewables, some of the physical constraints of power systems turn more complex** than they are for traditional, highly-centralized, stock-energy-based[5], power systems (Krakowski, 2016).

[5] That is, whose production plants are based on energy stocks such as coal, water in altitude, uranium, gas… as opposed to energy flows such as wind, flowing water, sun radiations and so on.

II. Taking into account frequency stability

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

Frequency stability[6] reflects the fact that the global balance between supply and demand is achieved at all times. In case supply is lower than demand, spinning machines (also called synchronous machines) slow down hence system frequency decreases. On the contrary, if supply is greater than demand, spinning machines speed up hence system frequency increases (RTE, 2004).

Frequency variations can be caused by:

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

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

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

The ability of the system to adapt to the variations of supply and demand is called *flexibility*. **Downward flexibility** is its ability to cope with increasing frequency (through production reduction or consumption increase, see Figure 1). **Upward flexibility** is its ability to regulate decreasing frequency (through increasing production or decreasing consumption). These frequency variations can be expected (e.g., expected increase of demand, or of production) or unexpected (EDF R&D, 2018).

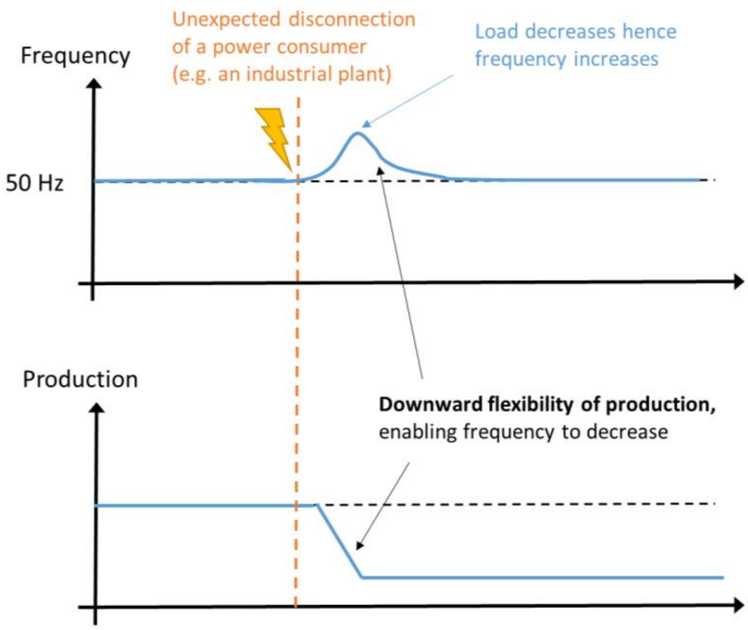

Figure 1: Illustration of downward flexibility lever activation following the disconnection of an important load (for example and industrial plant being disconnected). Source: The Shift Project.

Flexibility has two components (EDF R&D, 2018):

[6] In alternative current (AC) power systems, electricity parameters oscillate at a given **frequency**, reflecting the frequency at which spinning machines producing, and consuming electricity, spin

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

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

In this section, we talk about flexibility assuming that total capacity is enough to meet demand. In other words, we consider flexibility at forecast horizons shorter than the year.

The yearly flexibility (that is, the long-term adaptations of the PS to ensure supply-demand balance, usually called verification of total capacity) is considered in section about structural demand-supply balance (LTT).

Flexibility may be considered for different voltage levels as the uses associated to different levels are different. For example, electric industrial processes, electric train powering (subway systems, train systems…) require high power levels hence they are connected to high voltage parts of the grid.

C. A flexibility need for each forecast horizon

Flexibility needs can be categorized as follows, depending on their forecast horizon (EDF R&D, 2018):

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

D. Several kinds of levers to fulfill these needs

In order to fulfill these needs, flexibility levers exist. They can be gathered in four categories (EDF R&D, 2018):

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

- **Load management and demand response** within the industry sector, tertiary sector, or housing sector: this kind of flexible load is already able to provide flexibility services (reserves acting on the load side). Load management gathers three levers:
    - load shedding: consumer decides to cancel its consumption for a short time. This decision can be locally compensated by the use of another source of energy (for example a fuel engine-generator).
    - load delay: load is automatically delayed (such as for French storage water heaters)
    - demand turn up: consumers are asked to turn up their consumption. This service is asked in case of extreme downward flexibility needs.

  Load management capacity depends on market rules and regulations which determine the interest a consumer has to accept a management of her consumption. The development of load management depends on its competitiveness against other means to ensure grid constraint management and on the evolution of technologies enabling load management.
  Demand response is based on the behavior of consumers in reaction to live price signals. The ability of consumers to react to price signals depends on the information they have about their consumption and the prices. Hence with proper incentives, price signals can be organized such as to provide flexibility services. As discussed in the section about long-term transition of the PS, these levers may lead to desirability issues.
- **Storage devices**, in particular hydro power (traditional or pumped-storage) or electrochemical storage (batteries), can provide flexibility services. Storage can provide downward flexibility (by storing up energy) and upward flexibility (by injecting electricity). The different flexibility services it can provide depend on the type of storage through its key characteristics: energy capacity and power capacity, as well as swear patterns. Storage can also participate in grid constraint management. However, electrochemical storage is not economically competitive yet compared to a solution based on RESV curtailment (ensuring downward flexibility at low cost) and CCGT (ensuring upward flexibility at low cost, even with a carbon price). This situation depends on the market design and the revenues for different flexibility services. EVs, as storage devices, can participate in flexibility services.
  Similarly, P2X technologies[7] can participate in flexibility services.
- **Variable Renewable Energy Sources (VRES, composed of photovoltaic systems (PV) and wind turbines)**: they could provide flexibility services with proper adaptation of their inverters (see below). However their variability limits their ability to do so and requires good forecasting capabilities. VRES curtailment is a downward flexibility which should be taken into account when designing the PS, as an alternative to grid reinforcement (grid constraint management).

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

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

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

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

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

[7] P2X is the set of processes converting electricity in another potential energy which can be stored: power to heat, power to gas, power to fuel, power to products or power to liquids (EDF R&D, 2018)

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

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

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

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

Conventional synchronous generators (or Synchronous Machines, SMs), as well as rotating load devices include a turbine system and rotating components exhibiting mechanical inertia, and as such they are capable of storing kinetic energy in this rotating mass. Because that energy can be extracted from or absorbed into these rotating masses during system disturbances, an interconnected system of machines is able to withstand fluctuations in net load and generation. For example, reducing the speed of a nuclear plant 1.6 GW alternator from 1500rpm to 1470rpm requires the same amount of energy as stopping 22 40-tons trucks running at 100km/h[8] (EDF R&D, 2018).

Load significantly participates in inertia. As a consequence, if load evolves to more electronically coupled engines instead of directly coupled motors, PS inertia will decrease[9] (Eto et al., 2018).

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

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

Reserves are composed of:

- **Frequency Containment Reserve** (FCR, ENTSO-E naming), or primary reserve, automatically triggering action in participating plants (or consumers) within a few seconds. Its goal is to restore the production-consumption balance, stabilize the frequency and limit its fall (or rise). In the European power system, the upward FCR must represent 3 000 MW, which corresponds to the power of the two biggest power units.
  In case inertia is not high enough, a very fast reaction to frequency variation should be automatically triggered (within a second or so) at production or load level. This emerging need is called Fast Frequency Containment Reserve (Fast FCR)[10].
- **Automatic Frequency Restoration Reserve** (aFRR), or secondary reserve, enabling to restore the frequency to 50 Hz and the exchanges through interconnections
- **Manual Frequency Restoration Reserve** (mFRR) and **Replacement Reserves** (RR), or tertiary reserve. They are manually activated in order to replace the preceding reserves and get back to the initial reserve situation. (EDF R&D, 2018)

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[8] Inertia in the European PS is between 20 and 30 mHz/s (this frequency variation rate is called rate of change of frequency). In other words, if a synchronous generator is suddenly disconnected, the global frequency of the PS does not decrease faster than 30 mHz/s. (EDF R&D, 2018)

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

[10] A few PSs are already calling for larger Fast FCR, such as the PJM network in the North East of the US or National Grid UK

A key moment in the control is when FCR takes over when frequency starts to drop. The speed at which it must react depends on the system inertia: the lower the inertia, the faster the FCR must be in order for frequency not to drop too low[11] (Eto et al., 2018).

If frequency drops too low, rolling blackouts[12] are triggered. If frequency changes too fast or spikes too high, many equipment of the power system are automatically disconnected, which might lead to blackouts. (EDF R&D, 2018)

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

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

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

- **VRES variability impacts season to infra-day horizons flexibility needs**.
    - At day to infra-day horizon, the greater the VRES share, the shorter the duration of flexibility needs, but the greater their magnitudes. Also, with more VRES, the more often they will produce in excess, hence the more often downward flexibility will be required (see Figure below, source (EDF, 2015)). When flexibility is talked about in most reports about VRES integration, it generally means infra-hour flexibility, because flexibility needs at this time horizon are impacted by the integration of VRES. In particular, stronger ramp up means are required to compensate for fast decreases of VRES production.

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

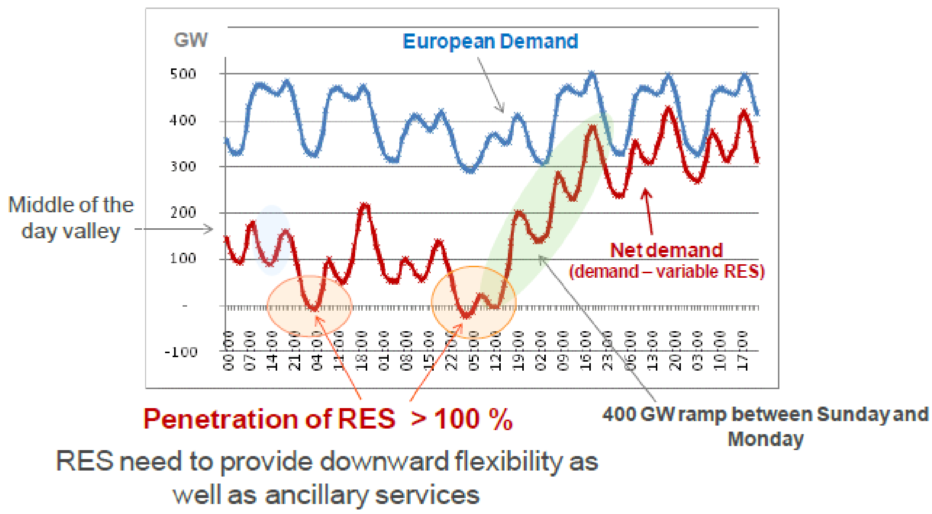

Figure 2: Power demand as modeled with a 60% share of VRES in the European power system. Power consumption at the European scale is represented in blue. Net demand is represented in red. Net demand represents power consumption minus the power which is produced by VRES. In other words, net demand is the consumption which must be satisfied by power production means other than VRES (traditional power plants + storage means). On this curve, net demand is negative when too much power is produced by VRES. A strong need for ramp up capacity.is highlighted in green.

    - At season horizon, the more VRES, the more inter-season flexibility will be required. Indeed, in Europe VRES tend to produce in excess in spring and summer but produce too little in winter.
- **The larger the geographical perimeter of the PS, the lower the variability of production at global scale** (aggregation effect). Wind and PV generation present an intermittent generation profile at

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

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

site level but as a result of natural geographical diversity this intermittency can be reduced when total production is considered at regional or national level. However, wind regimes are often somewhat correlated across Europe (Krakowski, 2016). Thus at the European system level a significant variability in the output of wind generation as a function of atmospheric conditions is observed. Conclusions are similar for PV (EDF, 2015).

- **VRES uncertainty impacts reserves needs**. VRES rely on weather-related energy. The more VRES in the PS, the more the production relies on weather events, hence the greater the uncertainty about production[13]. This uncertainty is reduced when weather forecast accuracy is improved. It is also reduced when the geographical perimeter of the PS is larger. Indeed chances are low that uncertainties of local productions all materialize as forecast mistakes at the same time and in the same direction. In other words, local uncertainties taken together in one interconnected PS do not add up.
- **Inertia decreases with more power electronics inverter connected plants, as VRES**. Nowadays the spin of a wind turbine is disconnected from the frequency it injects on the grid through the inverter, in order to optimize its power production (EDF R&D, 2018). By nature, PV power is not produced through a spinning machine and is connected through inverters (BMZ Deutsche GIZ GmbH, 2013; Kroposki et al., 2017). Inertia issues appeared on ERCOT power system in Texas (Matevosyan, 2017) and on Eirgrid in Ireland (O'Sullivan, Power, & Kumar, 2013), leading to curtailing VRES production in order to ensure a minimal level of inertia.

A decrease in inertia may be counterbalanced by a faster FCR. Hence a need for faster FCR could appear in scenarios with a high share of VRES (EDF R&D, 2018).

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

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

1. Inertia can be provided by synchronous machines, synchronous compensators and by VRES connected through grid-forming inverters associated with energy buffers

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

Maintaining inertia can be achieved by installing synchronous compensators (see Figure 3), which are synchronous machines running without producing electricity. They are useful to bring their inertia to the system (EDF R&D, 2018). They can provide all the ancillary services of conventional generators except those requiring active power, i.e. they can provide fault current, inertia and voltage support (see following sections) just like a synchronous generator. (Brown et al., 2018)

[13] Note that power demand has some regularity through time but is also uncertain. However, the uncertainty of power demand is much lower than that of VRES production thanks to a long history of consumption (Krakowski, 2016).

Figure 3: a synchronous compensator at Templestowe substation, Melbourne Victoria, Australia (source: Wikimedia Commons)

Another lever to bring inertia to the PS is to connect VRES through *grid-forming inverters* with sufficient energy buffers. The operation of power systems integrating such technologies is studied through experimentations and simulations by several academic and corporate teams (Matevosyan et al., 2019).

In these inverters, a set of algorithms enable it to mimic the physics and control laws of Synchronous Machines (SMs) in terms of stability (EDF R&D, 2018). This solution requires an energy buffer which replaces for a few seconds the kinetic energy that a SM would have provided.

For example, wind turbines can provide such a buffer for a limited amount of time (about 5-10 seconds), by suddenly reducing rotor's speed and transforming the corresponding kinetic energy into electric energy (Eto et al., 2018). Similarly, electric batteries associated with a grid-forming inverter can provide such a response. Supercapacitors can also do the job (Matevosyan et al., 2019) . Another way to provide such a buffer is to decrease the energy output of the inverter for wind turbines or PV even though they produce more (the extra capacity is called headroom), in order to keep the extra energy available as a buffer. Most likely, a combination of these buffers, depending on the concrete power system and location within it, will be required.

Grid-forming inverters do not tackle by themselves the issue of the availability of energy: in other words, PV farms and wind turbines must be producing to bring their inertia, just as for conventional power plants.

It is estimated by the latest research that an all inverter-based power system could properly operate under all known adverse contingencies if 10 % to 30 %[14] of the inverters are grid-forming (Matevosyan et al., 2019). For a synthesis on the control and operation of such a PS, see (Prevost & Denis, 2019).

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

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

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

Another point is that very fast reserve must be sustained until tertiary reserve takes the lead, which may take more than 10 minutes. During that time, VRES must be producing if they are to actually participate as very fast reserve.

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[14] In terms of capacity connected at each moment. That is, if 100 GW are connected to the power system at a given moment, 10 to 30 GW of them connected through grid-forming inverters are sufficient to provide enough inertia.

Thus VRES inverters, if carefully designed and under the previous conditions, can provide primary response that is faster to the response from conventional generators because of the fast-response speed from the power electronics interfaces (Kroposki et al., 2017). In other words, current VRES inverters (grid-following) lead to a decrease in PS inertia but in the meantime they bring in a greater dynamics to react to adverse contingencies.

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

As developed above, modeling challenges arise for scenarios implementing large shares of VRES, as VRES largely modify flexibility needs and also partly constitute levers. These challenges must be tackled as taking into account flexibility needs can significantly change the overall power system: for example, more conventional power plants may be integrated, or specific types of batteries may turn bankable (Krakowski, 2016).

We reviewed how future studies tackle this challenge as of today.

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

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

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

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

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

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

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

Inertia is rarely considered in future studies.

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

However, the inertia of load (that is, inertia of spinning devices which consume the electricity) has to be considered: simulations showed that the lower the load, the greater the required amount of system synchronous penetration (EDF, 2015). Inertia of the load is not considered in the future studies we reviewed. This may lead to biased estimates of inertia requirements. E.g. too loose dynamic thresholds may be used for low load levels. In addition, load could significantly evolve during the transition, affecting inertia requirements: if load evolves to more electronically coupled engines instead of directly coupled motors, PS inertia will decrease[16] (Eto et al., 2018).

A method to compute the global kinetic energy of a power system has been proposed in (Drouineau, 2011).

No future study to our knowledge proposes to connect VRES through grid-forming inverters (still an emerging technology), which may largely reduce the need for precisely simulating inertia.

4. The extreme cases of PSs operating without synchronous machines

A few studies present scenarios in which the PS operates only with inverted-connected plants at certain times of the year. Generally their scenarios assume a RES share of 80% to 100% of the annual energy production, including hydropower, biogas, CSP or other renewable technologies based on synchronous machines (ADEME, 2015; Association négaWatt, 2014; Fraunhofer ISE, 2015; Greenpeace, 2015; Lappeenranta University of Technology / Energy Watch Group, 2017; WWF, 2011).

However, those electric renewable technologies based on synchronous machines may not produce all the time. The case may happen that only inverter-connected VRES provide 100% of the electricity at certain times of the year.

Specific constraints apply in this case: no frequency based on the physical inertia of rotating masses is provided anymore. Without overcoming this, the PS would be highly unstable. A technical solution would be to provide an

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

electronic "beat-leader" that production plants could follow. Grid-forming inverters (see section II.H.1.) provide such a capability.

Also, inertia would drop to zero, so that the fast FCR would not prove fast enough (it would need an instant reaction time). Grid-forming inverters also solve this issue.

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

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

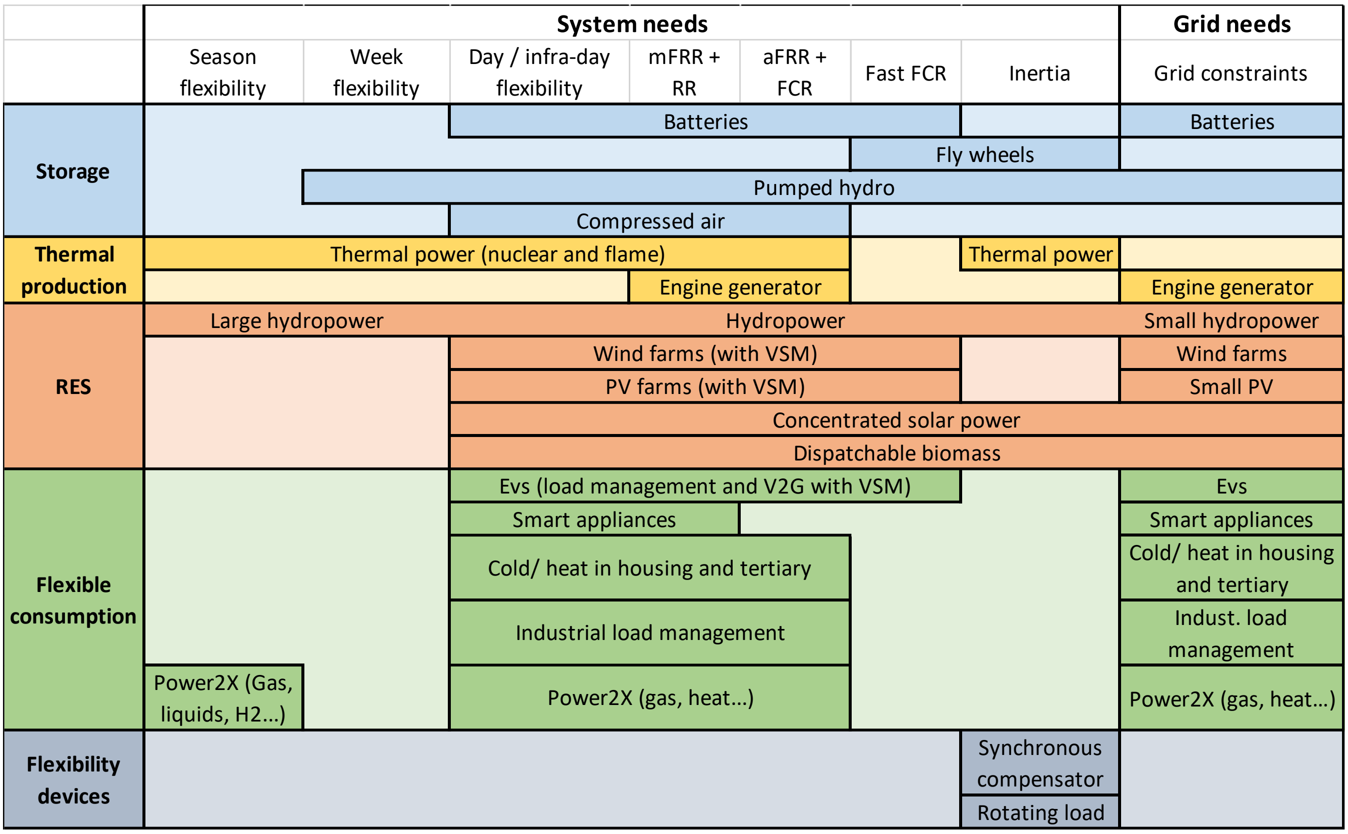

Figure 4: already available, and potential flexibility levers against the needs they can each fulfill (EDF R&D, 2018). Reading key: Storage technologies can provide different services of flexibility. For instance, fly wheels can provide fast FCR and inertia.

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

At all forecast horizons, increasing the geographical perimeter of the PS in addition to ensuring a proper centralized control of flexibility levers leads to a reduction in flexibility needs through aggregation effect. (EDF R&D, 2018)

L. Are smart grid technologies flexibility levers?

New smartgrid technologies, such as new grid forecast management solutions[17], advanced control functions and smart meters represent opportunities to manage flexibility needs at global and local scales. However, a local management of flexibility needs could lead to a suboptimal global management. The effects of local management of flexibility is still under study. In all cases, local management requires a close partnership between TSOs and DSOs (EDF R&D, 2018).

Recommendations on dynamic demand/supply balance

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

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

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

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

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

- Considered categories (forecast horizons) of flexibility needs: their list should be made transparent and justified with regards to the study strategy. *For example: What forecast horizons are considered in the scenario for evaluating the balance between needs and offer? In what respect is it useful to consider these horizons and not others with regards to the study strategy?*
- Considered voltage levels in flexibility needs: their list should be made transparent and justified with regards to the study strategy. *Are uses requiring high voltage (industrial processes, train systems…) considered?*
- Considered flexibility levers: their list should be made transparent and justified with regards to the study strategy. *Are batteries included? Demand response techniques?*
- Considerations on the coverage of the flexibility needs by the levers during the tested years, and on the indicators to convey this information, such as: is the obtained lever mix sufficient to cover the considered needs? If not, what are the impacts? These considerations should be provided for all the forecast horizons which are considered in the scenario. *For example: over the set of considered test years, are the needs fulfilled by the proposed levers' mix? If not, how often is the mix insufficient? What are the impacts of the insufficiencies on public perception, on economic criteria…? What would be the main trade-offs to consider to get a better coverage in the scenario?*
- Overall methodology used to assess the level of demand and supply balance for the different forecast horizons which are considered in the study. Methodological guidance can be found in (Krakowski, 2016).
- Specific considerations in case of very high shares of VRES, about inertia and what defines frequency when no synchronous machines operate. *Are their specific technologies enabling to define and stabilize frequency (grid-forming inverters)? How is inertia ensured?*

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

- Time pattern of levers' activations through the year and for each considered forecast horizon; activation mechanisms if they significantly differ from current ones. *For example: When, and how much, is the wind production curtailed? When do wind turbines participate in upward flexibility?*

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

- In particular, day-ahead to infra-day activation patterns are sometimes extensively described in scenarios (hour-per-hour description of power production and consumption, including storage pattern). A strategy about day-ahead activation patterns should be explicited.
  The following aspects could be described: Load, power generation, storage (consumption and production), demand-response and load management.
  Those aspects can be described per technology (or another disaggregation level depending on the driving questions), per region (or another resolution depending on the driving questions), and/or per type of actor. For example, demand-response activation could be described per type of actor (industry, households…).
  Other indicators could be provided, such as loss indicators (*how much loss, including curtailment, for each tested year?*); full load equivalent operating hours for production units, transmission load factor for relevant lines, or power import/export indicators.

- Available flexibility levers with regards to the technological storyline, for each considered forecast horizon. *For example: What levers are considered in the scenario (batteries, thermal power units, load management…)? In the scenario time frame, when does each of them start to be available? Is it consistent with the technological storyline?*
- Characteristics of flexibility levers, such as operating constraints (ramp up and ramp down capabilities, minimal or maximal operating points…), their costs, their impacts on society, how society adopts them (see section on desirability), or the environment, etc. *For example, depending on the study strategy: what are the characteristics of batteries with regard to flexibility (energy capacity, power, life duration as a function of use…)? How much lithium is required for the production of one battery? What amount of load management is available? What impacts on the desirability of transition?*
- Evolution of these characteristics through the scenario. The origin of these evolutions: technological (for conventional generators, storage devices and VRES) and / or behavioral (for load management and demand response). *For example: Do cost, technical characteristics and resource consumption of batteries evolve through the scenario? If yes, what does explain these evolutions?*
- Flexibility markets, for different forecast horizons. *For example: What are the considered market incentives for developing flexibility levers in the scenario? Are there any evolution of the flexibility market in the scenario?*
- Flexibility needs evolution through the scenario, such as: the total capacity for each considered forecast horizon, the frequency at which the need appears, the emergence of new flexibility needs. These needs depend on the weather-dependent share of production and on weather forecast performances. *For example: What evolution of the need for inertia during the scenario timeframe? Does a need for Fast FCR appear during the scenario timeframe? What evolution of the need for reserves? What evolution of the frequency of call of reserves?*
- Evolution of flexibility levers capacities per type of lever; geographical locations of the levers. *What evolution of the number of PV farms with VSM inverters in the scenario? What evolution of the installed capacity of such farms? Where are these farms located?*

M. Taking into account the quality of electrical waves is a secondary issue for future studies

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

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

These waves can be damped by installing filters, which **induces extra, but limited, costs**. Their variety and complexity make simulation and forecast studies about them difficult. More research is needed to precisely evaluate the extra-costs of damping these waves as necessary (EDF R&D, 2018).

Recommendations on sine waves quality

A scenario strategy about sine wave quality should be defined and justified. It should include considerations on the decision to study this subject or not. If the strategy is to discard this aspect, a qualitative analysis of the limitations it induces in the study should be performed. For example, elements explaining that solutions are available at a limited cost could be provided.

In case the subject is studied, the following aspects may be reported about:

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

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

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

III. Taking into account voltage control

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

Voltage is the parameter in a power system that indicates whether there is a **reactive power**[18] **imbalance in an area of a system** (BMZ Deutsche GIZ GmbH, 2013).

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

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

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

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

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

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

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

Voltage stability can be decomposed within two components:

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

Reactive power decreases with travelled distance. Hence it is more efficient to correct voltage variations very close to consuming devices (that is, at the level of distribution grid). However, control at the transmission grid level is required as it provides the frame within which the distribution grid operates. Control capabilities are also installed at the interface between the two grids through tap changers[19], and then in the distribution grid through passive devices (capacitors).

At the **transport grid level**, conventional generation plants provide a voltage control capability, each up to a certain point. Hence they are a simple and efficient lever for voltage control. In Europe, this service is remunerated through contracts with TSOs, or is regulated by law in order to get connection clearance (Julia Merino, Inés Gómez, Elena Turienzo, & Carlos Madina, 2016). These plants should be smartly located on the grid in order to ensure an

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

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

efficient control everywhere (RTE, 2004). However, in case they do not provide enough reactive power, other reactive power compensation means exist:

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

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

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

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

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

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

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

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

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

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

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

- Reactive power cannot be transferred over long distances but must be made available locally. However, especially wind farms are very often located in remote areas (remote from load centers). For this reason, even if wind farms are able to deliver reactive power, it may not be made available at the location where it is actually needed.
- The connection of generation plants to the distribution grid (also known as decentralized, or embedded generation, for example small scale RES) requires adaptations of the voltage control system (Heard, Brook,

Wigley, & Bradshaw, 2017; IRENA, 2017). Indeed, voltage control has originally been designed for centralized power systems[20]. Hence if more power production is connected to distribution grid, transmission grid will have to adapt its control mechanisms (EDF R&D, 2018).

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

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

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

Recommendations on voltage control

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

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

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

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

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

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

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

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

IV. Considering rotor angle stability

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

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

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

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

Two contingencies can lead to a rotor angle instability:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Recommendations to scenario producers on rotor angle stability

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

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

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

V. Considering other ancillary services

A. Short circuit current

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

Short circuit current is the current which is measured in case of the worst short-circuit fault[21]. It is composed of the currents coming from the sources which are in opposition to the fault.

Different types of power sources contribute differently to fault opposition. A Synchronous Machine can oppose perturbations by injecting up to 6 times its current rating. Inverter-connected VRES can contribute between 1.1 to 1.6 times their current ratings, due to the physical characteristics of interrupters composing the inverter[22].

(EDF R&D, 2018; Kroposki et al., 2017)

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

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

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

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

Another impact of low short-circuit current levels is a difficulty in starting big industrial electrical motors, which consume 6 to 7 times more current when they are being started than when they run[23].

3. Possible evolutions: adding short circuit current sources, updating fault sensors or making the protection system “smart”

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

- Synchronous compensators could be installed at relevant locations and bring the missing short-circuit current. However this solution may not be the most economical (Brown et al., 2018)
- Over-current detection could be replaced by differential protection and distance protection, both of which are established technologies (Brown et al., 2018)
- Over-current detection could be updated by adding a flow-direction detection capability (EDF R&D, 2018)

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

[22] Some grid-forming inverters can deliver up to 2 times their current ratings, slightly reducing the considered issue (Matevosyan et al., 2019).

[23] Synchronous generators can solve the problem. Another solution would be to equip industrial motors with electronical speed variators to decrease the starting current, albeit at an extra cost. This would however decrease load inertia which is useful for frequency stability (as mentioned p10).

- The protection system could be made "smart" by allowing a communication between all the detection devices. However, this would induce extra costs, cybersecurity concerns and resilience issues. (EDF R&D, 2018)
- The architecture of the protection system could be re-designed and modified taking into account the new connections (and those available technologies). (EDF R&D, 2018)

Recommendations to scenario producers on short circuit current

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

The following aspects may be reported about:

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

B. Fault ride-through capability

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

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

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

Recommendations to scenario producers on fault ride-through

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

The following aspects may be reported about:

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

C. Black-start capability

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

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

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

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

2. Black start capability for high VRES mixes: an issue linked to that of protection device

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

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

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

For scenarios with an inverter-dominated PS, black start must include a beat leader giving the frequency on which all other power plants can "connect". Indeed, the usual frequency beat provided by regulated conventional power plant (synchronous machines) can become too weak to efficiently operate. This long-term question seems to be currently answered thanks to grid-forming inverters associated with sufficient energy buffers (Matevosyan et al., 2019).

Recommendations to scenario producers on black start capability

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

Here are some of the aspects which may be studied:

- Black starting ability: equipment participating in this service, potential associated extra costs, evolution of the ability in the scenario time frame, potential impacts of a longer black starting time
- Beat leader presence especially with very high shares of inverter connected generators: equipment ensuring it within the scenario time frame (*grid-forming inverters associated with sufficient energy buffers?*), potential associated costs

VI. Planning for market designs and regulations: a near-term challenge but a secondary issue for future studies

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

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

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

In Denmark, markets have been created for short-circuit power and for reactive power. (EDF R&D, 2018)

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

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

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

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

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