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Power Transmission & Distribution Systems

Flexibility needs in the future power system

Discussion paper

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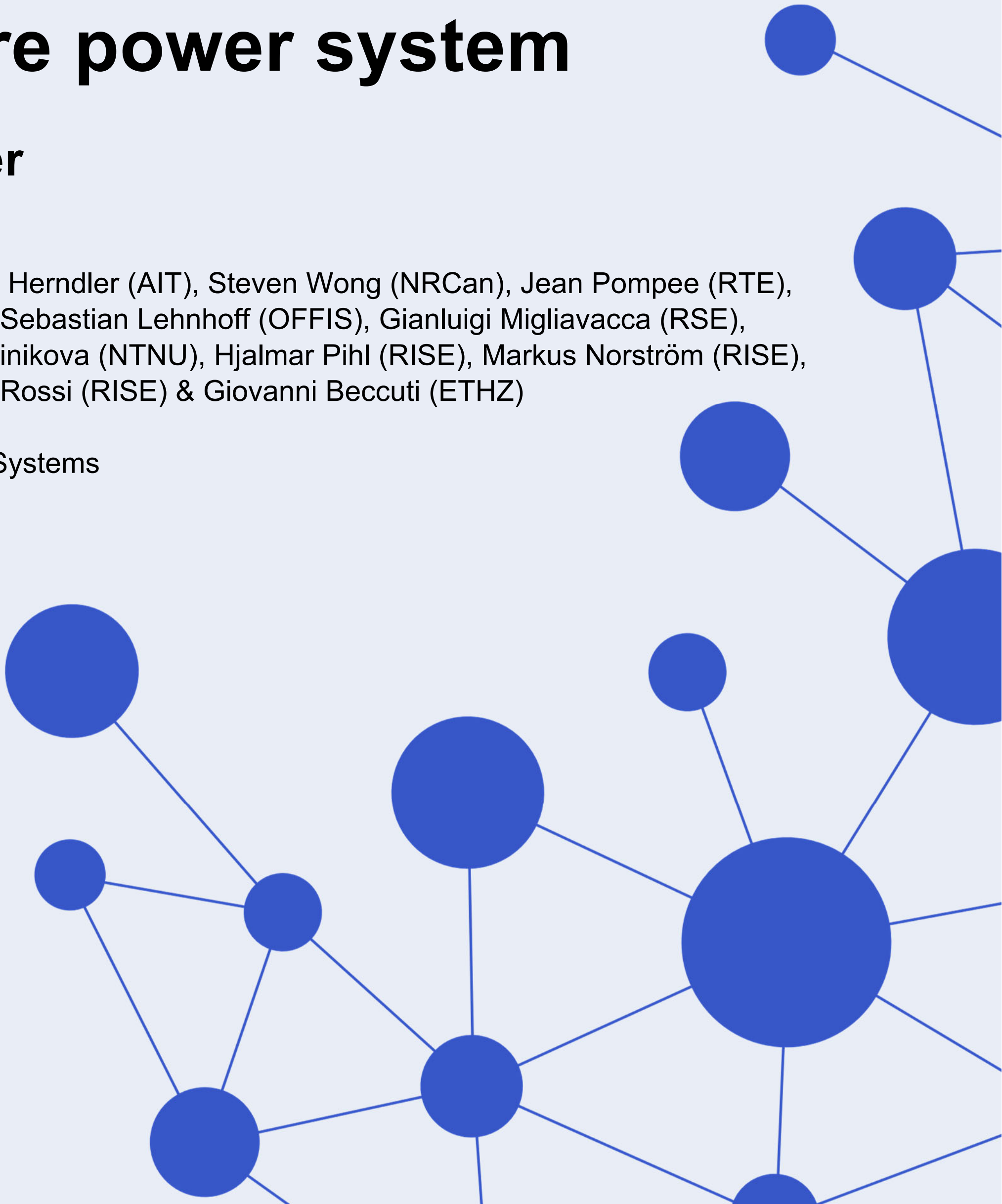

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List of Acronyms

aFRR	automatic Frequency Restoration Reserve
AS	Ancillary Service
AVR	Automatic Voltage Regulator
BESS	Battery Energy Storage System
CHP	Combined Heat and Power
DER	Distributed Energy Resources
DFR	Distributed Flexibility Resources
DLR	Dynamic Line Rating
DR	Demand Response
DRI	Direct Reduction Iron
DSM	Demand Side Management
DSO	Distribution System Operator
DSR	Demand Side Response
ETS	Electric Thermal Storage
EV	Electrical Vehicle
EWH	Electric Water Heater
FACTS	Flexible AC Transmission System
FCR	Frequency Containment Reserve
FFR	Fast Frequency Response
HVDC	High Voltage Direct Current
ICT	Information and Communication Technology
mFRR	manual Frequency Restoration Reserve
OLTC	On-Load Tap-Changer
PSS	Power System Stabiliser
PST	Phase-Shifting Transformer
PV	Photovoltaic
RES	Renewable Energy Sources
SGAM	Smart Grid Architecture Model
SIPS	System Integrity Protection Scheme
SoS	Security of energy
SPS	System Protection Scheme
STATCOM	STATic synchronous COMpensator
SVC	Static var Compensator
TSO	Transmission System Operator

Executive summary

Power system flexibility relate to the ability of the power system to manage changes.

Solutions providing advances in flexibility are of utmost importance for the future power system. Development and deployment of innovative technologies, communication and monitoring possibilities, as well as increased interaction and information exchange, are enablers to provide holistic flexibility solutions. Furthermore, development of new methods for market design and analysis, as well as methods and procedures related to system planning and operation, will be required to utilise available flexibility to provide most value to society.

However, flexibility is not a not a unified term and is lacking a commonly accepted definition. Several definitions of flexibility have been suggested, some of which restrict the definition of flexibility to relate to changes in supply and demand while others do not put this limitation.

The flexibility term is used as an umbrella covering various needs and aspects in the power system. This situation makes it highly complex to discuss flexibility in the power system and craves for differentiation to enhance clarity.

In this report, the solution has been to differentiate the flexibility term on needs, and to categorise flexibility needs in four categories:

- **Flexibility for Power:**
  Need Description: Short term equilibrium between power supply and power demand, a system wide requirement for maintaining the frequency stability.
  Main Rationale: Increased amount of intermittent, weather dependent, power supply in the generation mix.
  Activation Timescale: Fractions of a second up to an hour.
- **Flexibility for Energy:**
  Need Description: Medium to long term equilibrium between energy supply and energy demand, a system wide requirement for demand scenarios over time.
  Main Rationale: Decreased amount of fuel storage-based energy supply in the generation mix.
  Activation Timescale: Hours to several years.
- **Flexibility for Transfer Capacity:**
  Need Description: Short to medium term ability to transfer power between supply and demand, where local or regional limitations may cause bottlenecks resulting in congestion costs.
  Main Rationale: Increased utilisation levels, with increased peak demands and increased peak supply.
  Activation Timescale: Minutes to several hours.
- **Flexibility for Voltage:**
  Need Description: Short term ability to keep the bus voltages within predefined limits, a local and regional requirement.
  Main Rationale: Increased amount of distributed power generation in the distribution systems, resulting in bi-directional power flows and increased variance of operating scenarios.
  Activation Timescale: Seconds to tens of minutes.

Here, flexibility needs are considered from over-all system perspectives (stability, frequency and energy supply) and from more local perspectives (transfer capacities, voltage and power quality). With flexibility support considered for both operation and planning of the power system, it is required in a timescale from fractions of a second (e.g. stability and frequency support) to minutes and hours (e.g. thermal loadings and generation dispatch) to months and years (e.g. planning for seasonal adequacy and planning of new investments).

The categorisation presented in this report, supports an increased understanding of the flexibility needs, to be able to identify and select the most suitable flexibility solutions.

Given a functional flexibility market, flexibility resources are able to compete against each other with their specific technical advantages and constraints.

Coordination between TSOs and DSOs is essential to ensure that flexibility resources in distribution networks remain available for balancing purposes without inducing unmanageable local congestions, which could jeopardize the local grid.

An optimal mix of flexibility resources can be obtained through a holistic approach considering technical, commercial and environmental aspects.

Given a long term stable and permissible regulatory framework, with an innovative and transparent market environment: properly designed systems for measurement, information and communication, monitoring, control and protection, can provide key solutions for flexibility which is increasing needed in the future power systems.

Table of Content

1. Introduction

This report is prepared within the framework of ISGAN Annex 6 (http://www.iea-isgan.org/our-work/annex-6/). The work of Annex 6, on Power Transmission & Distribution Systems, promotes solutions that enable power grids to maintain and improve the security, reliability and quality of electric power supply. This report is the outcome of an activity within the focus area *Technology Trends and Deployment*. The main objective of this focus area is to identify the potential and feasibility of new technologies, to prioritize the need for further development, and to make recommendations on how to stimulate demonstration and deployment of promising technology options. Figure 1 positions this work in the ISGAN context.

ISGAN (http://www.iea-isgan.org)

ISGAN is the short name for the International Energy Agency (IEA) Implementing Agreement for a Co-operative Programme on Smart Grids (ISGAN). ISGAN aims to improve the understanding of smart grid technologies, practices, and systems and to promote adoption of related enabling government policies. ISGAN's vision is to accelerate progress on key aspects of smart grid policy, technology, and related standards through voluntary participation by governments in specific projects and programs.

ISGAN Annex 6

ISGAN Annex 6 - **Power Transmission and Distribution Systems** focuses on both transmission and distribution systems related challenges in the development of Smart Grids.

ISGAN Annex 6 Focus area Technology Trends and Deployment

The main objective of this focus area is to identify the potential and feasibility of new technology, to prioritize the need for further developments and to make recommendations on how to stimulate the demonstration and deployment of promising technology options.

Discussion paper on Flexibility of the future power system

The discussion paper provides an insight into the concept of flexibility, including some of the major rationales, together with an overview on recent developments and ongoing initiatives related to flexibility from a multi-dimensional perspective.

Figure 1 Position of this report in ISGAN context

The goal of this report is to provide an increased understanding of the topic of flexibility in operation and planning of the future power system.

Section 1 provides the background information and formulates the reasons as to why flexibility has become topical in the energy sector and includes definitions of flexibility. In Section 2, we present a way to categorise flexibility needs for operation and planning to improve the clarity of the different flexibility concepts. Section 3 provides insights into recent developments, by presenting information from recent international projects or efforts, illustrating a broad international view on flexibility in the future power system. The last sections of the report include conclusions, discussions and references.

1.1. Background

The evolution of the power system has significant impact on the operation and planning of the future power system. Five major global trends influencing the evolution of the power system are [1]:

- **Decarbonisation** - Decreasing the carbon footprint from electric power production.
- **Decentralisation** - Transition from few and large, centralized, power plants to many smaller, decentralised, power production units.
- **Integration** – Increasingly integrated electricity markets, greater interconnection of previously independent grids, and more integrated energy systems including sector coupling.
- **Digitalisation** – Extensive implementation of and dependency on information and communication technologies and solutions.
- **Inclusion** - Increasing demand for sustainable, affordable and accessible energy for all including increased electrification of e.g. industrial processes and transport.

These trends bring challenges in planning and operating the power system in a secure and reliable manner, such as:

- **Identification of true operational state** - As the utilization of the power system is increasing, it becomes even more important to quantify uncertainties in measurements and modelling to better understand reserves to critical limits.
- **Changes in dynamic response -** As a result of power electronic (PE) interfaced devices taking over the roles of rotating machines, the dynamic behaviour of the power system changes and, as a result, commonly accepted rules and principles may no longer be valid.
- **New utilization patterns** - More dispersed generation units, new type of demand, increased number and size of interconnections, results in utilisation of the power system in new and previously unforeseen ways.

The flexibility of the power system is seen as a key to cope with some of the challenges of future power systems. Solutions providing advances in flexibility are of utmost importance for the future power system, making this an increasingly important topic to consider for operation and planning and for policy makers [2]. An example of this is illustrated in the ENTSO-E R&I roadmap 2017-2026, [3], having flexibility as one of five dedicated research area clusters.

Flexibility has been in focus for several years, with a large number of initiatives ongoing in various fields. The large number of recent publications on the subject further highlight its importance, as illustrated by the in-depth reviews presented in [4] and [5]. The increased need of flexibility relates largely to the significant increase of variable renewable resources as described in [6]. The Nordic TSOs have identified the need for flexibility as one of the main challenges in the near future [7]. Improved TSO-DSO coordination to utilise flexibility resources are discussed in [8]. ENTSO-E is further highlighting the importance of utilising flexibility from distributed resources, described as Distributed Flexibility Resources (DFR), in [9]. Strategies to utilise flexibility, available from power electronic interfaced generation and load, to enhance the stability and security of the power system is identified as a primary focus area for research and development [10]. An overview of flexibility for system support is presented in [11], and flexibility for forecast balancing are presented in [12] and [13].

Development and deployment of innovative technologies, communication and monitoring possibilities, as well as increased interaction and information exchange, are enablers to provide local, regional and system wide flexibility solutions. In order to utilise the available flexibility to provide the most value to society, there is a necessity for the development of new market solutions and utility practices as well as enhancement of existing market rules, which includes both short-term and long-term markets [1].

Earlier work from ISGAN Annex 6 related to the flexibility of the power system include:

- “TSO-DSO interaction: An Overview of current interaction between transmission and distribution system operators and an assessment of their cooperation in Smart Grids”, [14]. This report presents proposed solutions to utilize flexibility, to prevent congestions and to support voltage and grid balancing, through coordinated interaction between distribution and transmission system operators.
- “Storage and balancing as key elements for future network planning and electricity markets design”, [15]. This report presents an analysis of the flexibility contribution that could be provided by storage participating in the energy markets and through trans-national coupling of balancing markets.
- “The role and interaction of microgrids and centralized grids in developing modern power systems – A case review”, [16]. This report describes possibilities of interaction between micro-grids and central grids, which may serve as additional flexibility providing value to all. Furthermore, microgrids can be used as a flexible means of grid expansion since the construction rate may highly exceed the rate of expansion of a central grid depending on local regulations.
- “Flexible Power Delivery Systems: An Overview of Policies and Regulations and Expansion Planning and Market Analysis for the United States and Europe”, [17]. This report presents a study of policies and regulations in the United States and Europe and how these have developed over time. The purpose of this work was to identify how a flexible power delivery system may be achieved, and several opportunities are presented to overcome some of the challenges which the power systems are facing.
- “Smarter & Stronger Power Transmission: Review of feasible technologies for enhanced capacity and flexibility”, [18]. This report presents the development and deployment of technologies to enhance the capacity and flexibility of the transmission system.
- ”Single marketplace for flexibility”, [19]. This report presents a proposed market structure to handle flexibility in a coordinated and transparent manner between TSOs and DSOs. A summary of this work is presented in Section 3.2.
- ”System efficiency”, [20]. This report presents insights into initiatives addressing efficiency-related aspects in future electricity grids. Looking at how flexibility resources in different areas can provide additional degrees of freedom to improve the system efficiency. A summary of this work is presented in Section 3.3.

With several of the previous ISGAN Annex 6 reports highlighting the subject of flexibility in one way or another, this report intends to provide a deeper understanding of flexibility with the primary focus being on the needs required in operation and planning of the future power system.

1.2. Definition of flexibility in the power system

Flexibility has both technical and commercial dimensions, where the technical capabilities may be utilized to support the grid and the system in accordance to the commercial capabilities of the markets and their regulations.

Even though it may seem commonly accepted that flexibility relates to the ability of the power system to manage changes, flexibility is not a not a unified term and is lacking a commonly accepted definition. Several suggested definitions are available, and some of these are gathered below.

In 1995, CIGRE through the working group 37.10, defined flexibility from the planner's perspective as:

> *"the ability to adapt the planned development of the power system, quickly and at reasonable cost, to any change, foreseen or not, in the conditions which prevailed at the time it was planned."* [21]

In 2011, the International Energy Agency (IEA) described flexibility as:

> *"the extent to which a power system can modify electricity production or consumption in response to variability, expected or otherwise. In other words, it expresses the capability of a power system to maintain reliable supply in the face of rapid and large imbalances, whatever the cause."* [22]

EURELECTRIC made a description of flexibility in 2014, [23]. This description was adopted by the European Commission Smart Grids Task Force to form the definition of flexibility as:

> "*the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system."* [24]

EPRI, the Electric Power Research Institute, defined flexibility in 2016 as:

> *"the ability to adapt to dynamic and changing conditions, for example, balancing supply and demand by the hour or minute, or deploying new generation and transmission resources over a period of years."* [25]

In 2017, CEER (the Council of European Energy Regulators) made a public consultation to provide definitions of flexibility. As answers to this consultation, the European Transmission System Operators ETSO-E proposed the definition as:

> "*the active management of an asset that can impact system balance or grid power flows on a short-term basis, i.e. from day-ahead to real-time."* [26]

European DSOs also answered to the CEER consultation, basing their proposed definition on [23] and [24] and published this in [11] as:

> *"the modification of generation injection and/or consumption patterns, on an individual or aggregated level, often in reaction to an external signal, in order to provide a service within the energy system or maintain stable grid operation."* [11]

The final conclusions from CEER were published in 2018, with the proposed definition of flexibility as:

> "*the capacity of the electricity system to respond to changes that may affect the balance of supply and demand at all times.*" [27]

In 2018 IEA provided a revised definition of flexibility as:

> "*all relevant characteristics of a power system that facilitates the reliable and cost-effective management of variability and uncertainty in both supply and demand.*" [2]

The International Renewable Energy Agency (IRENA) defined flexibility in 2018 as:

> "*the capability of a power system to cope with the variability and uncertainty that VRE (variable renewable energy) generation introduces into the system in different time scales, from the very short to the long term, avoiding curtailment of VRE and reliably supplying all the demanded energy to customers*". [6]

Many additional suggestions for the definition of flexibility are available, also from the academy where e.g. [28] consider flexibility to represent a systems

> *"ability to accommodate the variability and uncertainty in the load-generation balance while maintaining satisfactory levels of performance for any time scale."*

Analysing these suggested definitions, it is noted that several restrict the definition of flexibility to relate to changes / modifications in supply and demand, while others do not put this limitation. Furthermore, the broad range of meanings of the suggested definitions lead to the general statement that:

Flexibility relate to the ability of the power system to manage changes.

In a sense, this statement illustrate that the flexibility term is used as an umbrella covering various needs and aspects in the power system. This situation makes it highly complex to discuss flexibility in the power system and craves for differentiation to enhance clarity.

In this report, the solution has been to differentiate the flexibility term on needs, and to categorise flexibility needs as presented in Chapter 2.

2. Categorisation of flexibility needs in the power system

This section is intended to provide an increased clarity into the concept of flexibility through categorisation of flexibility needs in the power system.

In this report, flexibility needs are considered in a holistic manner, both from the overall system perspectives as well as from the more local perspectives:

- Flexibility needs from an overall system perspective are related to maintaining a stable frequency and a secure energy supply.
- Flexibility needs from a more local perspective are related to maintaining bus voltages and securing transfer capacities.

This means that flexibility needs and resources may be found in the whole power system.

Solutions to provide flexibility in this sense are not limited to modification in supply and demand. On the contrary, many different type of solutions may provide value to increase the flexibility of the power system where solutions to influence rules and regulations in operation and planning of the power system may provide significant value to increase the flexibility. Similarly, needs for flexibility are not only limited to the balance of supply and demand, but are also for relevant for maintaining voltages and securing transfer capacities.

In this report, flexibility solutions are considered for needs in both operation and planning of the power system. Thus, the timescales relating to flexibility range from fractions of a second to years.

It is important to understand the flexibility needs to be able to identify and select the most suitable flexibility solutions and the resources which can provide the flexibility. The most suitable flexibility solution is dependent not only on the need, but also on: situational restrictions and regulations, and on available power system equipment. Selection processes may include technical, commercial and environmental aspects, considering type of loads as well as available generation units, storage solutions, DC connections to other systems, etc.

Depending on the need, possible flexibility resources are required locally or can be provided from the whole power system. Examples of possible flexibility resources include: Operational and planning procedures; Synchronous conventional power plants; Power electronic interfaced renewable power plants; Grid infrastructure primary equipment; Grid infrastructure secondary equipment; Energy storage; Demand; Sector coupling. Based on the concept of Security of energy supply, [29] suggest how services of flexibility resources may be classified.

When considering flexibility for both operation and planning of the power system, flexibility support is required in a timescale from fractions of a second (e.g. stability and frequency support) to minutes and hours (e.g. thermal loadings and generation dispatch) to months and years (e.g. planning for seasonal adequacy and planning of new investments). Detailed insights in timescales and resources are presented in [2] and [6].

Categorisation of flexibility needs are in this report done through four categories: *Flexibility for Power, Flexibility for Energy, Flexibility for Transfer Capacity,* and *Flexibility for Voltage*.

The interrelation of the four categories in the dimensions of time and space are presented in Figure 2, with a few examples of flexibility solutions for each category provided in Figure 3.

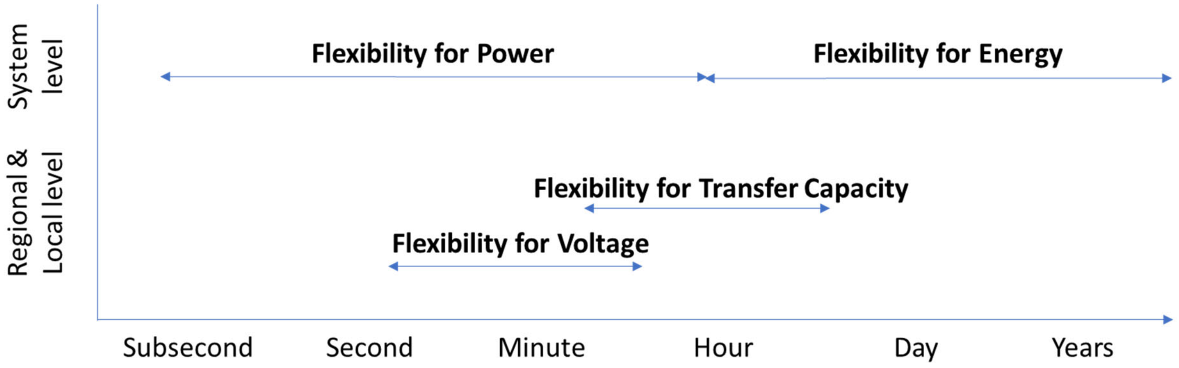


Figure 2 Interrelation of flexibility needs in perspectives of space (local/regional to system level) and time

The timescale of Figure 2 represent the requirements in activation time for the flexibility need. The ranges illustrated for the four categories are approximate and are dependent on the physical behaviour of the system as well as on requirements and regulations.

In the perspective of space, the categories are separating needs which are local or regional (*Flexibility for Transfer Capacity* and *Flexibility for Voltage*) from needs which are system wide (*Flexibility for Power* and *Flexibility for Energy*).

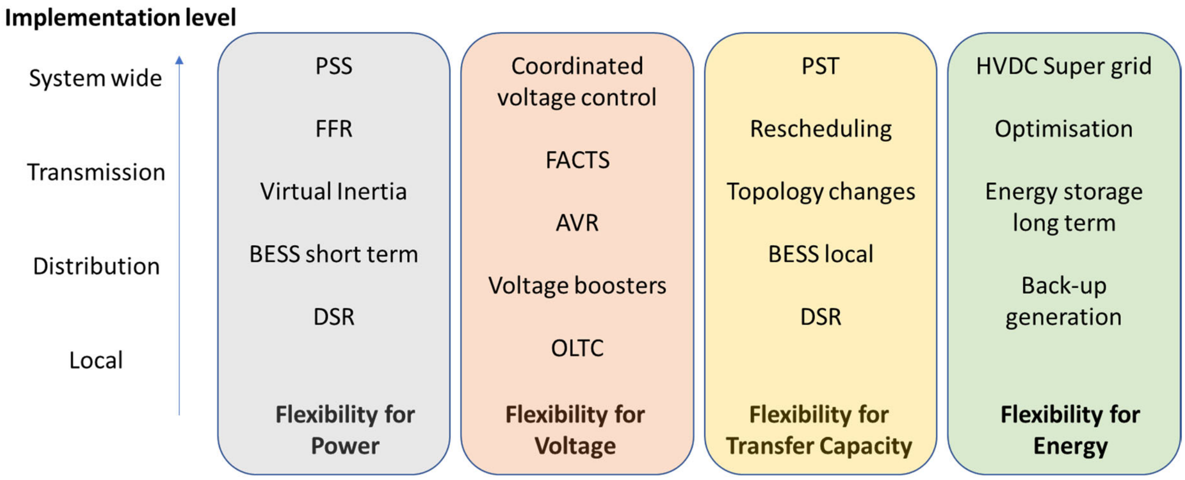


Figure 3 Examples of flexibility solutions for each category with implementation levels from local to system wide. (PSS: Power System Stabiliser; FFR: Fast Frequency Response; BESS: Battery Energy Storage System; DSR: Demand Side Response; FACTS: Flexible AC Transmission System; AVR: Automatic Voltage Regulator; OLTC: On-Load Tap-Changer; PST: Phase-Shifting Transformer)

The examples of flexibility solutions presented in Figure 3 are a mix ranging from system services, control-based responses, operational procedures, to implementation of new power components in the system. These solutions are implemented on different hierarchical levels in the system, from the local level through the distribution and transmission system levels, to the system wide level. It should be noted that resources can be used as flexibility solutions for more than one of the categories.

Each of the four flexibility categories are described in the following sub-sections, with the last sub-section dedicated to an example of how flexibility may be quantified.

2.1. Flexibility for Power

Need description: Short term equilibrium between power supply and power demand, a system wide requirement for maintaining the frequency stability.
Main rationale: Increased amount of intermittent, weather dependent, power supply in the generation mix.
Activation timescale: Fractions of a second up to an hour.

A functioning power system is required to maintain the equilibrium between power supply and power demand at all times. For the short term, this corresponds to maintaining the system frequency within pre-defined limits in order to prevent frequency instability (in an AC system). Conventional means of maintaining the frequency relate to the control of active power of generation units within the synchronous area. This is defined as the units balancing capability (upward or downward, depending on the requirement of increasing or decreasing the power generation). The balancing capabilities within a system are defined by the flexibility of the generation units. Control of flow on DC connections to neighbouring systems may also be considered to provide a part of this balancing capability. Furthermore, system demand has also been part of the balancing capability through the incorporation of bi-lateral agreements with dedicated load centres to decrease their demand if required.

Increasing the amount of intermittent weather dependent power generation, which results in the decrease of available plannable generation, increases the uncertainties and variability of the power supply. To be able to maintain a secure future supply of power, there is an increased need for flexibility solutions to provide balancing capability:

- For the remaining plannable generation units, this may result in requirements of increased flexibility of e.g. thermal power plants to widen their operating ranges (minimum load levels and ramping rates) and shorten their start-up time.
- For the intermittent power generation units, flexibility requirements may result in a requirement to provide upward and downward balancing capability implying curtailment of renewable energy.
- To utilise a large number of small production units and loads, aggregated control of supply and demand may be used to provide flexibility solutions.
- Furthermore, solutions may involve the utilisation of short-term storage units and interaction between multi-energy carrier systems.
- Evaluating possibilities of increasing limits within which the system is operated, e.g.: minimum/maximum frequency deviation; speed of frequency changes (rate-of-change-of-frequency); amount of time outside acceptable limits, may also prove to be suitable solutions for flexibility. Such changes may also cause altered requirements of the units and systems within the power system.

The flexibility need categorised as *flexibility for power* is required to support the system within fractions of a second up to an hour.

2.2. Flexibility for Energy

Need description: Medium to long term equilibrium between energy supply and energy demand, a system wide requirement for demand scenarios over time.
Main rationale: Decreased amount of fuel storage-based energy supply in the generation mix.
Activation timescale: Hours to several years.

For the medium to long term, the equilibrium requirement between supply and demand implies the requirement to secure the supply of energy for future scenarios.

Managing and maintaining a secure energy supply in the long-term perspective is complex and involves seasonal optimisation of the value of stored energy including forecasted outage periods for power plant maintenance, future load scenarios, etc.

Conventional solutions include stockpiling of fuels for thermal plants and the use of hydro reservoirs to reduce the impact of seasonal variations in precipitation and load. Seasonal variations in load are also considered when scheduling appropriate timing for the maintenance of the traditional base-load thermal units (such as nuclear and coal), in such way that long-term flexibility is provided and thus maximising the availability for high demand seasons.

Pumped hydro is a flexibility solution for daily demand variations, to utilize available generation capabilities during hours with low demand in order to increase the amount of supply available for hours with high demand.

Photovoltaic (PV) solar energy production have a strong seasonal variation in countries far from the equator and has a negative correlation with weather dependent loads in colder climate.

Decreasing the amount of fuel storage-based energy supply (such as nuclear and coal) and increasing the amount of non-fuel storage based energy supply (such as solar and wind), increases the uncertainty of the future energy supply. To be able to maintain a secure future energy supply, in a medium- and long-term perspective, there is an increased need for flexibility solutions to provide possibilities of storing energy from situations of high supply to situations with low supply.

Altering the demand behaviour, to follow variations in supply, may provide part of such flexibility on the daily perspective but likely not significantly on the seasonal level.

The flexibility need categorised as *flexibility for energy* is required to support the system in the multi-hour, daily, seasonal and annual perspective.

2.3. Flexibility for Transfer Capacity

> *Need description*: Short to medium term ability to transfer power between supply and demand, where local or regional limitations may cause bottlenecks resulting in congestion costs.
> *Main rationale*: Increased utilisation levels, with increased peak demands and increased peak supply.
> *Activation timescale*: Minutes to several hours.

Dealing with power system security, the topology and capacity of the power grid plays a most important role. As grids are typically dimensioned and planned in a socio-economic way, with available grid capacity placing restrictions on operation and operation planning. Thus, flexibility does not only relate to the ability to balance supply and demand, but also to the location of reserves to be activated given a certain disturbance or unbalance and the grid capacity between the demand and supply.

Flexibility is, to a certain extent, a built-in functionality in the power grid itself. In an AC system, the use in operation of real-time or anticipated changes in grid topology (so called “remedial actions”) is a well-known and cost-free flexibility resource. Besides, other measures which provide increased transfer capacities or flexibility in the control of the power transfer system are available in operation like increasing nominal voltage levels, or the use of phase-shifting transformers. At the grid expansion planning stage, series-compensation, or, power electronics based Flexible AC Transmission Systems (FACTS) devices can be installed. They can be used to control voltage, re-direct power flows or to improve stability properties.

New installation to strengthen the power transfer may not be possible or justifiable from different perspectives. Such limitations may occur locally and regionally, influencing the power system on a national and international level. In such cases, other solutions to increase the flexibility for transfer capacity may be needed to cope with increasing peak transfer situations.

System integrity protection schemes (SIPS or SPS) may be used to increase transfer capacities. Such protections may be designed to act as a response to an event, in order to prevent or limit the extent of a disturbance.

Dynamic line rating (DLR) for overhead lines increases the flexibility in utilization of assets, where the use of measurement system solutions provide ambient dependant utilization levels of lines instead of predetermined fixed ratings. Utilizing dynamic rating for other assets, such as cables, may be future solutions which may increase the flexibility to cope with peak transfer situations.

Time variable transfer tariffs are possibilities to influence the behaviour of demand and supply, in order to prevent congestion during peak transfer situations.

Power systems are usually operated and planned in accordance with the *n-1* reliability criterion, implying that no single contingency should result in a large disturbance. The *n-1* criterion imposes restrictions on power transfer, where e.g. thermal or stability limits of lines places constraints on transfer on parallel connected lines in a power transfer corridor. Such limitations may lead to bottlenecks in the system and result in regional price difference for customers or limitations on generation. The *n-1* criterion is quite simple to implement but does not consider the relative probability or the consequence of a specific outage.

Furthermore, power systems may be subject to multiple or “cascading power transmission outages”. Such outages may propagate nonlocally; after a fault occurs on one component, the next fault may be very distant, both topologically and geographically. In the end, such propagation may get out of control and lead to system wide blackout. In order to avoid such events, additional restrictions may be imposed on power transfers in which case limitations are due to security concerns rather than thermal ratings.

The use of probabilistic reliability criteria instead of, or as complements to, the *n-1* deterministic criteria could provide additional flexibility for transfer capacity and further increase the available grid capacity. Such approach has been investigated in the GARPUR project, [30]

The flexibility need categorised as *flexibility for transfer capacity* is required to support the local and regional grid, which means that the location of resources to provide the flexibility is highly important. The timescale relevant for *flexibility for transfer capacity* is in the ranges of minutes to several hours.

2.4. Flexibility for Voltage

> *Need description*: Short term ability to keep the bus voltages within predefined limits, a local and regional requirement.
> *Main rationale*: Increased amount of distributed power generation in the distribution systems, resulting in bi-directional power flows and increased variance of operating scenarios.
> *Activation timescale*: Seconds to tens of minutes.

Maintaining the bus voltages within predefined levels throughout the power system is important both from a stability perspective as well as for power quality.

Voltage stability is largely related to the reactive power capabilities of generation units, and other reactive power compensation units, and the location of such units. The behaviour of demand, as well as the operation of distributed generation units, has a strong influence on the voltage.

FACTS devices, such as static var compensators (SVC) or static synchronous compensators (STATCOM), are increasingly important as means for TSOs or DSOs to control voltage and at the same time being flexible and independent of services from generators.

The increased amount of distributed generation creates completely new power flows in the system, altering voltage profiles in the distribution system and may lead to decreased power quality. To be able to maintain the bus voltages within predefined levels, there is an increased need for flexibility solutions to provide voltage support.

Ancillary services from distributed generation and storage may become useful solutions for distributed voltage support. Demand side response solutions may be used in a similar way.

Broadening of acceptable ranges for power quality may also prove to be suitable solutions for flexibility. Such changes could lead to increasing requirements on components and systems within the power system.

The flexibility need categorised as *flexibility for voltage* is required to support the power system on a local and regional level, which means that the location of resources to provide the flexibility is highly important. The timescale relevant for *flexibility for voltage* is from seconds to tens of minutes.

2.5. Quantifying the need of flexibility in the power system

Since flexibility may be defined in a variety of ways, it is difficult to quantify the total need of flexibility. Instead, limiting the focus only to a certain type of flexibility may allow it to be quantified. Some of the quantifiable dimensions of flexibility are:

- Power – physical capability to deliver, e.g. the size of the flexible active or reactive load, expressed in MW or Mvar
- Response time – the time until the flexibility can be delivered, e.g. related to start-up time of a power plant, expressed in seconds-minutes-hours-days-years
- Speed – the rate of which the flexibility can be delivered, e.g. emergency ramp rate of an HVDC, expressed in e.g. MW/s
- Duration – how long the flexibility can be provided, e.g. the time span for overload rating of a component, expressed in seconds-minutes-hours etc.
- Energy – merging the power and duration dimensions, expressed in e.g. MWh
- Recovery period – the time interval needed to provide flexibility after it has been fully utilised, e.g. the time to fully charge an empty energy storage, expressed in seconds-minutes-hours etc.

A list of flexibility metrics for long-term planning purposes can be found in [13], where a methodology for quantifying flexibility requirements is proposed using flexibility metrics Flexible Power Requirement [MW] and Flexible Energy Requirement [MWh], for daily, weekly and annual timescales.

Another example of quantification of flexibility is presented in a study made for the Swedish smart grid forum [31]. There are several flexibility aspects quantified in [31], one of which is related to the hour of the year with the maximum load “the peak-load hour”. During that hour (in Sweden typically a weekday morning during one of the coldest winter months January or February) the need of flexibility may relate to plannable power supply, power import and transfer capacities, and the possibility of time shifting demand. The way that flexibility has been quantified in this study is through assessing the difference between national production and consumption during the peak-load hour for a “10-year winter”, i.e. the power balance (expressed in MWh per hour). The results of this quantification are presented in Table 1. The negative sign on the power balance implies that the forecasted demand is larger than the forecasted available production.

Table 1 Quantification of flexibility needs: power balance for the peak-load hour in Sweden

“10-year winter”	Power balance [MWh/h] from [31]
2017/2018	-850
2025	-3000
2035	-5000
2040	-8000

The results in [31] for the winter 2017/2018 are based on the adequacy forecast study made by the Swedish TSO Svenska kraftnät [32] and are used in the assessment of the power balance of future winters. An interesting reflection is that in the updated prognosis from 2018 [33], Svenska kraftnät have revised their way of assessing the power balance for the peak load hour. This changed prognosis results in a significant increase of the imbalance, as shown in Table 2.

Table 2 Prognosis of power balance for the peak-load hour in Sweden

“10-year winter”	Power balance [MWh/h] from [33]
2018/2019	-1500
2020-2023	-3500

A conclusion from this example is that the increased need for flexibility (in the context of adequacy in power balance for the peak-load hour) in the future Swedish power system is considerable where a large amount of the plannable nuclear production in Sweden is foreseen to be phased out. In [31], significant increase of international power transfer is foreseen to cope with these flexibility needs.

This example further illustrates the large uncertainties related to the forecasting of future scenarios.

3. Developments of solutions for flexibility in the future power system

This section gives insights into recent developments and future focus areas of flexibility in the power system. The subsections present information from recent international projects or efforts divided into:

Market mechanisms; Coordination between TSO and DSO; Over-all energy system sustainability; Value of standardised communication; Residential Loads; Research development and demonstration examples.

3.1. Market mechanisms to enable better utilization of available flexibility

The primary objective of the markets is to establish competitive situations, particularly preventing the creation or the strengthening of market power or prohibiting the abuse of a position of substantial market power. The competitive conditions should be established in the markets and competitive constraints which the market actors face should be eliminated, meaning that a competitive market should be established. This role of the market is directly tailored to the changing manner of system operation and utilization to obtain higher system efficiency. Figure 4 presents an overview of different energy markets and market forms.

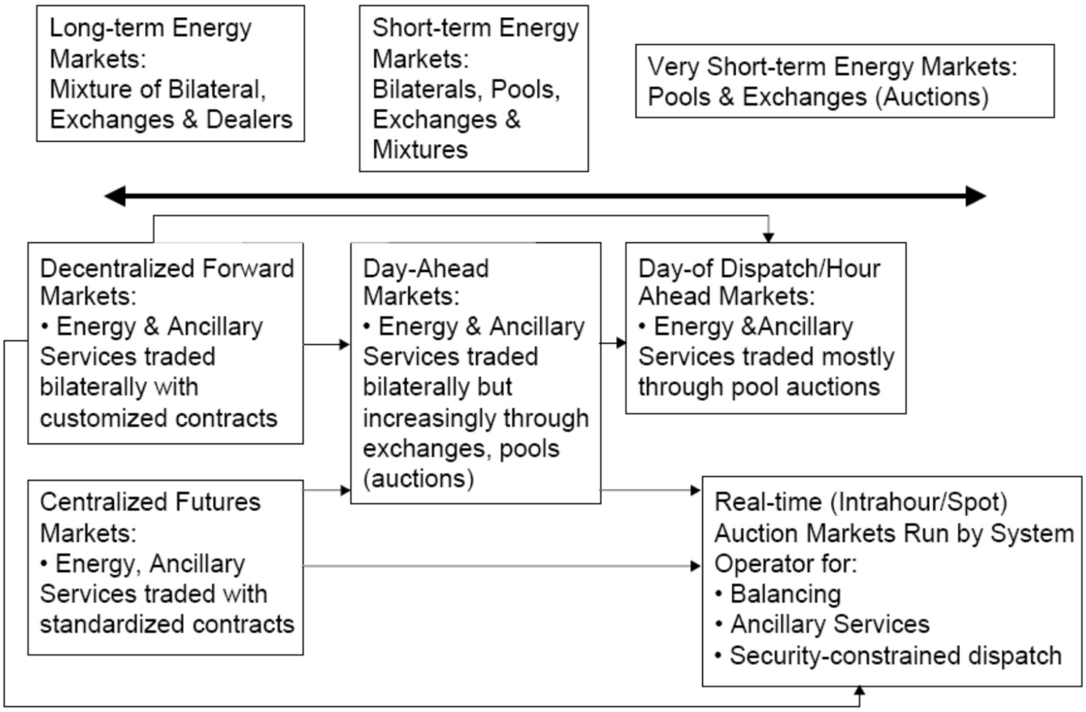


Figure 4 Overview of different markets

The following sub-sections provides a description of the need for proper market mechanisms and models for flexibility from different market perspectives.

3.1.1. Price formation

The issues related to the question of how to determine electricity prices (pricing) has been and still are addressed. The fundamental specific problem of pricing electricity is its requirement to maintain balance between supply and demand, in real time, in all places (nodes) of the power system. The most significant benefits from the introduction of spot prices assumes improvement of economic efficiency of investments into power system infrastructure and more rightful allocation of costs and benefits for all market participants. Basic considerations in formulation of the spot price concept are:

- Dependence on electricity prices over time;
- Dependence of price on the location of electricity supply or demand (consumption) in the power systems;
- Stochasticity of supply and demand functions in terms of time and space;
- The impact of a particular configuration of power system (networks) to the price of electricity.

3.1.2. Incentives and stimuli

Investments into overall new infrastructure are no longer centrally planned. Market prices should provide the right incentives for the development of the network and for investing in new electricity generation. However, stimulation of investors with reliance only to market signals can be not sufficient for proper, stable and sustainable development of the power system. Targets, and thus investments, are often different (opposed) regarding to independent market players. Therefore, possible regulation and standardisation implications for market design must be identified.

3.1.3. Economic trends and future grid investments

Production and consumption trends imply that a substantial share of the grid investments will be made in order to avoid congestions that are expected to occur for only a few hours each year. Hence, the full load hours of these grid assets are likely to be rare. It is economically optimal to make investments in new grid capacity when the willingness to pay for the increased capacity is higher than the costs of making the expansion. According to economic theory, the price of a good should be set above the short-run marginal cost when demand exceeds capacity. Such scarcity pricing in the grid means that network customers with the lowest willingness to pay reduce their load first. In cases where the grid approaches its capacity limit, it may therefore be an alternative to introduce scarcity pricing in order to provide an optimal utilization of the grid capacity. When the revenues from scarcity pricing approaches the long-term marginal cost of grid expansion, the grid capacity should be expanded.

Only a few relevant contributions can be found in economic literature relating to the issue mentioned above. Most articles on markets for local flexibility are primarily concentrated at the short-term balancing solutions of distributed renewable generation, and to a lesser extent with how local flexibility can be used as a substitute for grid expansion. Most of the schemes discussed in the literature requires real-time operation and a relatively sophisticated DSO function but does not recommend a concrete market design [34].

The criteria for a market solution for local flexibility can be formulated as follows:

1. Short-term efficiency: Does a market solution for local flexibility yield a more efficient utilization of resources than the current solution?
2. Long-term robustness: Does a market solution for local flexibility cater for reduced grid investments?
3. Efficient competition: Will there be sufficient market liquidity and participants to achieve efficient price formation?
4. Neutral: Who should operate the market platform?
5. Overall system efficiency: Can the flexibility resources be used for other purposes as well?
6. Practical feasibility: Do the benefits of a market solution merit the total costs?

3.1.4. Two-step approach for flexibility assessment

Regarding the methodology for flexibility assessment, a two-step approach is favoured by the French TSO RTE:

1. **Assessment based on the analysis of the fundamentals of power system economics:** This consists of applying the “benevolent monopoly” approach to power systems which is equivalent to the “perfect competition” balance. At this stage, the aim is to be able to take into account all relevant technical constraints and associated costs (technology, potentials, “natural” loads…), and try to maximize the social welfare of the considered zone. Where France is concerned, the relevant zone is Europe as a whole. This assessment will show the highest gain possible, which will be used as a baseline for further studies. The cost-benefit analysis enables highlighting optimisation impacts on potential local benefits effected by a broadened zone (for instance local markets vs European market integration).
2. **Introduction of forecast uncertainty, market players (and their strategies), market rules:** These constraints will yield outcomes with lower social welfare than that of the “benevolent monopoly” approach, however the possibility to compare with this reference enables the system and market designer to determine the main fields of improvement. At this stage, the way the added value is shared (redistributive effects among market actors) will also come into play, which is an essential criterion to identify individual stakes and efficiently promote the needed adaptations of rules.

In the context of a world-wide energy transition deeply affecting the whole power system, RTE is developing methodologies to add to these techno-economical perspectives a focus on systemic environmental impacts through life-cycle assessment.

3.1.5. Summary

In conclusion, it is important to underline that in order to provide flexibility to the power system there is a need of coordination between all market participants with solutions implemented in technically feasible and economic manners.

3.2. Coordination between TSO and DSO for utilisation of flexibility resources

An increasing need for flexibility is expected in the future, both on the transmission and on the distribution level. Part of this flexibility will be found at the distribution grid. Therefore, some framework to use distribution connected flexibility to support distribution and transmission network operation will be needed. The key requirement of such a framework is that the activation of flexibility by one system operator should not harm the grid operation of the other involved system operators.

In France, many flexibility resources (distributed generation, demand side management…) are connected to the distribution grid, but are activated by RTE within the balancing market, without major impact on distribution network operation. However, the current mechanisms (registration, activation) might not be sufficiently robust to incorporate a large increase of RES. By contrast, restricting the use of local flexibility for local grid management would represent a huge loss in balancing opportunities at the national (and European) level.

Balancing is essential to ensure safe operation of the power system (and hence the security of supply). Switching from a zonal to a local balancing would theoretically induce higher balancing costs, as achieving a large-scale optimum is always better than the sum of local optima. The key issue is to strike a balance between local congestions management and efficient and flexible access to balancing parties’ offers.

Therefore, RTE is investigating technical means of coordination with the DSO to ensure that distribution network resources remain available for balancing purposes without inducing unmanageable local congestions, which could jeopardize the operation of the local grid.

The ISGAN Annex 6 discussion paper on a Single Marketplace for Flexibility [19] investigated the possibility to install one marketplace in which all flexibility bids are collected and from which TSOs and DSOs could procure flexibility in a coordinated way.

The requirements for this marketplace have been identified as follows:

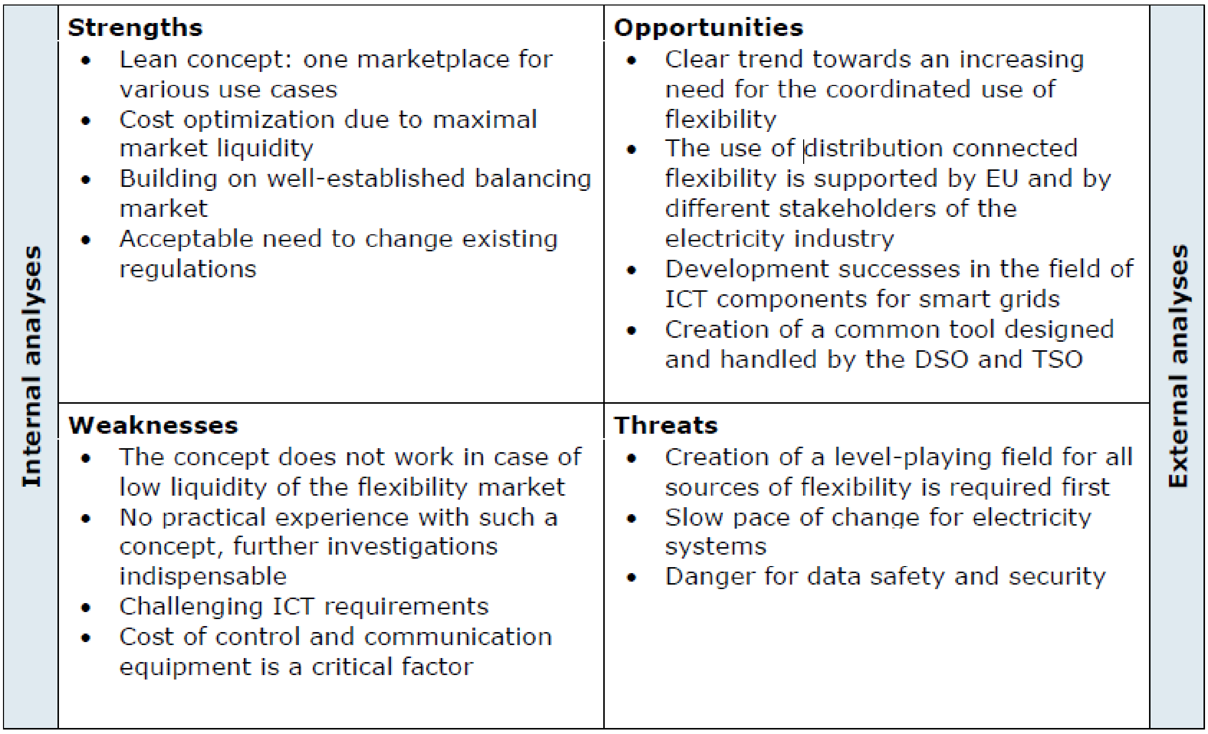
- Ensure effective market access for all market participants to valorise their flexibility, directly or through an intermediary
- Generate sufficient liquidity ensuring the procurement of all required capacities
- Enable information flows between TSOs, DSOs, Flexibility Service Providers and Balance Responsible Parties to allow network operators to coordinate their actions
- Meet high standards of data security and privacy

In terms of products, the TSO would be able to procure flexibility for balancing (FCR, aFRR, mFRR) and congestion purposes. The DSO would be able to procure flexibility for congestion purposes. The proposed implementation of this marketplace involves an information collection phase and negotiation phase, during which flexibility is procured through an auction, matching flexibility offers with flexibility needs while taking into account the technical boundary conditions of the system.

One obvious challenge is that a TSO and DSO might compete for the same resources. Due to the locational aspect, a DSO has no or few alternatives, whereas it is assumed that, in a liquid market, the TSO can procure alternative flexibility at the same or a marginally higher price.

An evaluation of the single marketplace concept can be found in the table below.

Table 3 Single market concept SWOT analysis



Internal analyses	**Strengths** • Lean concept: one marketplace for various use cases • Cost optimization due to maximal market liquidity • Building on well-established balancing market • Acceptable need to change existing regulations	**Opportunities** • Clear trend towards an increasing need for the coordinated use of flexibility • The use of distribution connected flexibility is supported by EU and by different stakeholders of the electricity industry • Development successes in the field of ICT components for smart grids • Creation of a common tool designed and handled by the DSO and TSO	**External analyses**
	Weaknesses • The concept does not work in case of low liquidity of the flexibility market • No practical experience with such a concept, further investigations indispensable • Challenging ICT requirements • Cost of control and communication equipment is a critical factor	**Threats** • Creation of a level-playing field for all sources of flexibility is required first • Slow pace of change for electricity systems • Danger for data safety and security	

The single marketplace is a lean and transparent concept to coordinate the procurement of flexibility between TSO and DSOs, which could theoretically lead to an economic optimum for the entire system, while respecting its technical boundary conditions. The concept builds on the existing market implementation in Europe, but the roles of the network operators, especially the DSO would need to evolve to be able to implement such a concept.

Apart from the possibilities the single marketplace concept offers, there are also some points of attention. A prerequisite for the concept to work is that a liquid market with sufficient flexibility offers is readily available. Moreover, the assumptions and simplifications made need validation, for example through a market-theory-based analysis.

3.3. Flexibility for overall energy system sustainability

In the recent past there has generally been a steady growth in the deployment of generation units in distribution grids, often based on renewable and non-controllable energy sources. One key constraint of electricity networks however is that production and demand must match at all times, prompting the need for novel solutions in the form of technologies, processes and regulations, to guarantee that the generated electrical energy can be utilized in a manner that does not jeopardize grid stability. Any proposed solution should also be economically efficient, since costly technologies and operating procedures are unlikely to be adopted in a competitive market setting.

It is specifically with respect to these issues that the ISGAN discussion paper on System Efficiency, [20], attempts to highlight and analyse ongoing initiatives, regulatory policies, and research and development work worldwide which address efficiency-related aspects in future electricity grids. Specifically, three efficiency dimensions have been selected:

1. CO_2: greenhouse gas (especially CO_2) emissions are avoided, or at least minimised
2. Energy: energy, especially from renewable energy sources (RES), is not wasted
3. Costs: economic costs are reduced, or at least not increased

Proposed solutions should aim at achieving an amelioration in at least one of these dimensions, preferably without negatively impacting any of the others. Although a precise quantification of the overall effects might be difficult to determine or might at best depend on a case-by-case analysis. Achieving this goal is only possible if one has the possibility of leveraging suitable flexibility resources, since it is precisely through the latter that additional degrees of freedom can be tapped with the aim of improving end performance. The following flexibility resources have been selected for methods targeted at system efficiency improvement:

1. Multi-energy systems
2. Electric storage
3. Electric mobility
4. Demand side management (DSM)
5. Automation & sensor technologies

Curtailment of renewable energy sources, although in itself a flexibility option, was not considered in this study. The material presented in [20] indicates that there is in general a significant amount of on-going activities at an international level and that there is considerable interest in developing and promoting flexibility approaches aimed at improving efficiency. Since the energy sector has historically been perceived as a somewhat conservative industry, it is furthermore important to underline that institutional support for innovation is often key to ensuring that novel methods and technologies are adopted in practice. Some highlights include:

- **Multi-Energy Systems:** Several activities and initiatives have been initiated in Europe and incentives have been developed aiming at the support of multi-energy systems and

associated technologies. There is currently an increase in the installation of heat pumps, also as a concrete consequence of such policies.
- **Electric storage:** Battery costs are still somewhat high but are also expected to decrease in the years to come, although an overall assessment of the entire life-cycle of these technologies would also come into play to evaluate their suitability for wide-scale deployment. One specific incentive for the installation of small batteries could be their joint utilisation with residential PV units. One such programme exists in Germany.
- **E-mobility:** Norway stands out for its E-mobility programme, which is also facilitated by the specific composition of an electrical energy system that almost entirely consists of hydropower with high storage capacity. Germany also appears to have a prominent role in this area, since it has a strong automotive industry for which it aims to develop a strong domestic e-mobility market. India has enacted a significant set of initiatives at both the national and local level with the explicit aim of achieving only EV sales by 2030.
- **DSM:** The measures adopted in the USA have had a considerable impact with respect to reducing the peak load, with a decrease of up to 30%, also due to significant support given to novel automation and sensor technologies. Research activities in Ireland are targeted in the same direction and a similar approach has been already implemented recently in Sweden. No specific information concerning the rebound effect was available at the time of writing.
- **Automation & sensor technologies:** the USA has attained significant improvements in terms of system efficiency thanks to the deployment of novel automation and sensor devices, which in turn has been made possible by a federal funding initiative of exceptional proportions. This emphasises the value that public incentives and subsidies can have on the adoption of innovative solutions.

Further details are available in the ISGAN discussion paper on System Efficiency [20].

It should be noted that when considering RES curtailment, there is no straightforward answer which the most efficient solution is. It can be easily shown that a larger RES installation, restricted from providing maximum output and subjected to curtailment, may provide more renewable energy to the system than a smaller RES installation. Thus, it is not evident that RES curtailment by definition is negative from both environmental and cost perspectives. A detailed case-by-case life cycle analysis is necessary to derive the most efficient solution.

Industrial users are currently seen as an important source of flexibility and are likely to become even more important in the future power system. The general pressure for a sustainable development and reduction of carbon dioxide emission from the industry leads to an interest to substitute fossil feedstock and fuels with different kinds of electrification. Electrification of industrial processes can be done directly as e.g. when replacing oil/gas for steam and heat purposes or indirectly as when e.g. electricity is used to electrolyze water into oxygen and hydrogen, where the latter is used as a feedstock rather than a fuel. The flexibility potential in the applications based on electrolysis and hydrogen is the largest due to the ability of electrolysers which can be ramped up and down to equalize fluctuations and that hydrogen as well as downstream intermediates can be stored in large volumes at a competitive cost compared to many other energy storage solutions.

There are many different industries such as steel, biofuel, cement, chemicals and plastic industries that could potentially combine their own strive to become carbon dioxide neutral by electrification and at the same time become a balancing agent of the power system.

One of the more advanced industries in Sweden in this development is the steel industry. They are planning to substitute fossil coke and fuel gas with renewable hydrogen by replacing the conventional blast furnace process with hydrogen reduction for DRI (Direct Reduction Iron) production, [35]. A full-scale deployment of hydrogen reduction within the steel industry would curtail around 10% of Sweden's carbon dioxide emissions and use about 10-15 TWh/yr of renewable electricity (about 10% of Sweden's total use of electricity) [36]. The steel industry is predominantly located in the northern part of Sweden, where there is a surplus of electricity, bottle necks in the transmission system and a high penetration of planned wind power is to be located. Hence, this would be an ideal spot for a balancing agent.

Decarbonization of the transport sector is in full swing and different pathways like EV, electric roads and biofuels are being explored and implemented. The biofuel industry is in strong growth and transformation and is, to a large extent, trying to utilize lignocellulosic feedstock (e.g. wood) for its expansion rather than the traditional fatty feedstocks due to availability and sustainability issues. Most process paths from lignocellulose to hydrocarbons require massive amounts of hydrogen, which for sustainability performance should be made from renewable electricity. Since there are many pathways to decarbonization of the transport sector, it is difficult to estimate the total potential electrical consumption and hence the potential to act as a source of flexibility. However, as an example from Sweden, the leading Swedish biofuel producer aims to produce 3 million m^3 biofuel yearly by 2030. This amount corresponds to their current Swedish sale of gasoline and diesel [37] and about 30 % of the total road transport fuel consumption in Sweden today. The specific amount of hydrogen needed for this biofuel production depends on the type of biomass raw material and production process used but is estimated to be at least 3 TWh/yr, corresponding to ≥ 300 Nm^3 hydrogen per m^3 biofuel product [37]. Given an efficiency in the electrolysis of 65-70%, this stream amount of biofuel production would require 4-5 TWh of electricity, which could be used as balance.

To fully harness the potential for flexibility from electrification of industrial processes, it is necessary to find a market model that compensates the industry for their capability to deliver to the power system in a fair, transparent and predictive manner. Such a market model would enable industries to invest in electrification and storage. Furthermore, it is imperative that the overall cost of electricity and the electrification process is competitive compared to the traditional processes and that availability of electricity over time is reasonable in spite of being a balancing agent.

RTE has been investigating for two years, in a collaboration with GRTgaz (the largest of the two French gas TSOs) multi-energy modelling and sector-coupling. A cross-sectoral analysis sheds light in particular on the flexibility needs of the whole energy sector. Furthermore, it paves the way to a coordinated use of existing flexibility resources, reducing the need for new investments.

For instance, the French gas sector's seasonal flexibility requirement amounts to more than 150 TWh per year, which is currently dealt with by natural gas import and storage. The use of natural gas is expected to decrease sharply between 2018 and 2050, in order to fulfil European decarbonisation targets. In terms of flexibility, full electrification would imply a massive increase in seasonal flexibility requirement (to say nothing of the consequences on the grid itself). Power-to-gas in coordination with additional RES capacities might be a sounder alternative, making use of the existing gas transmission infrastructure.

3.4. Value of standardised communication to facilitate communication to flexibility providers

From the Information and Communication Technology (ICT) perspective, the step-by-step integration of new stakeholders, devices and products into the European electricity system represents one of the great challenges of the energy transition [38]. Increasingly interconnected systems lead to a large number of new interfaces between different systems and growing amounts of data that need to be processed in smart electrical grids [39].

A central requirement for cost-effective system integration is the normalized use of technical standards for interfaces, data models and communication protocols, i.e. interoperability between systems from different vendors [40]. This is especially true for the integration of new vendors and stakeholders, e.g. flexibility providers.

Smart grids are power grids that promote energy-efficient and cost-effective system operation for future requirements. Due to coordinated management, they often make use of real-time two-way communication between grid components, producers, storage, and consumers. In order to lower technical integration costs, interfaces and data processes need to be standardized.

Three good reasons for driving interoperability and Integrating the Energy System:

- **Users**, also known as flexibility providers, have a strong interest in providing their services to various partners but small budgets and limited time to implement various types of interfaces to participate on markets
- **Vendors** have the same interest as users. Products and devices are not built for individual national markets, having standardized interfaces helps to enter new markets whereas proprietary data formats and communication are barriers for new parties
- **Distribution System Operators** have a stake, too. In order to cope with flexibility, direct control, planning and observability is of interest. DSOs cannot support various protocols from various vendors in their portfolio. Therefore, they have a strong interest in defining basic profiles for data exchange and communication in order to bring flexibility options into their operations portfolio.

In 2017, the project Integrating the Energy System Austria (IES), [41], has successfully taken the first step towards a European follow-up initiative on testing interfaces and providing means to check for standardized communications and profiles [42]. The aim is to continue creating profiles for communications based on a model from the health sector. IES strives to set up a joint transnational structure for a European organization called IES Europe in collaboration with partners from other European countries. Among the declared objectives are:

- **IES process**: Development of an annually recurring process chain that brings together vendors and users of smart energy system technologies
- **IES Europe**: Setup of a transnational organisational structure to coordinate the operative work throughout the IES-process
- **Connectathon Energy**: Hosting of annual European interoperability test events for users and vendors of ICT-systems in the energy sector

IES Europe is currently part of the European Strategic Energy Technology-Plan (SET-Plan) Implementation Plan *'Increase the resilience and security of the energy system'*, [43], and will run under the framework of the ERA-NET initiative.

The project aims to:

- Establish the IES-process on a European level, thereby linking national and European activities and ensuring an interoperable European energy transition
- Use synergies with existing European interoperability initiatives, e.g.: EIF, EIRA, ISA2, eIDAS
- Foster cross-border & cross-sector activities to support the creation of the Energy Union and the Digital Single Market, as pursued by the European Commission

The research combines best practice examples from energy and healthcare. The work is based on an existing methodology from ICT in healthcare (ISO/TR 28389), where interoperability of systems has long been achieved. Using the European Smart Grid Architecture Model (SGAM/M490) as a technical foundation, the IES approach will facilitate the development of a holistic IT architecture for the future European Energy system. The use-case centric approach ensures high flexibility of the applied method.

Integrating the Healthcare Enterprise (IHE), [44], is already a global initiative with the objective to achieve interoperability of ICT-systems in healthcare. IHE developed a fair, cooperative and participatory method to engage vendors, manufacturers and users alike. By initiating a cross-sector knowledge exchange, the IES team benefits from years of IHE-experience and know-how and can transfer this to the scope of smart distributions grids and future energy systems.

The European Smart Grid Architecture Model (SGAM) was developed by the Smart Grid Coordination Group (SG-CG) and the European standardization organizations CEN/CENELEC/ETSI in the context of the framework of the European Union's Mandate M/490, [45].

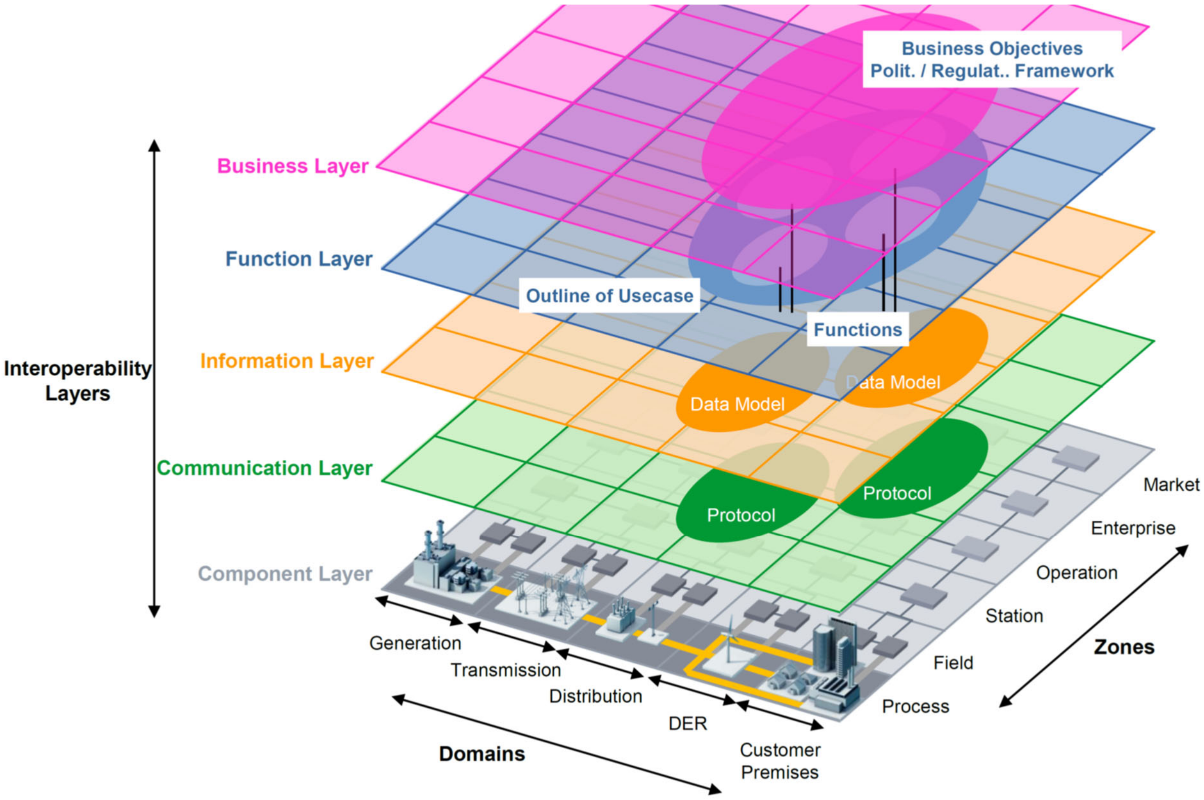


Figure 5: The European Smart Grid Architecture Model (SGAM), from [45]

The SGAM illustrates five interoperability layers on which the exchange of information in Smart Grids can be organised. Representing a recognised reference for classifying and discussing information systems and assets in the smart grid, the SGAM can serve as a basis for more in-depth architecture assessment and analysis for security, costs, technical interoperability and degree of standardization needed for technical interfaces in smart grids and the corresponding profiles for integration [46].

The research project IES strives to adapt and implement a vendor-neutral method to achieve interoperability of ICT-systems in smart energy systems [47]. In a cooperative process, vendors and users specify the normative use of existing technical standards for interfaces and communication protocols, such as the IEC 61850, to address well-defined use cases representing real-world interoperability issues [46]. Specifications are provided in 'integration profiles' that assemble specific 'base standards' which together provide complete technical specifications that cover all interoperability issues (e.g. data formats, transport protocols, vocabularies, security methods).

IES also develops a manual and guidelines for the practical implementation of the adapted process as well as a software tool for interoperability and conformity testing.

3.5. Realizing Flexibility from Residential Loads

Canada's residential sector consumes roughly a third of the electric energy used in the country; composed of many small individual loads, the majority serves space heating, space cooling, and water heating needs. These loads are relatively non-complex (compared to that of commercial loads or industrial processes) and are homogeneous for the purpose they serve (e.g., there is little variation in the basics of water heater operation). Many of the loads also have inherent storage potential.

Unlike conventional battery technologies (such as lithium ion) which have a primary role of providing storage to the grid, the storage potential of residential end-use loads is secondary to their primary role, that is, of serving an end use. For example, electric water heaters (EWHs) commonly have tanks to store hot water to ensure service during periods of high demand. The cost of capturing storage from these loads is primarily the marginal cost of the enabling technology, usually control and sensors (and providing a much cheaper alternative than dedicated battery technologies). Advanced demand-side management (DSM) strategies can use this storage to provide extra flexibility to the grid, with minimal impact to the end user [48].

3.5.1. Storage Potential

Figure 6 depicts the overall potential of common residential electric devices in Canada, as measured by availability, adjusted storage potential, and cost. On the y-axis is availability, a measure of the number of Canadian households with the given device. On the x-axis is device potential, as measured by seasonally adjusted storage potential (i.e., storage potential accounting for limited seasonal accessibility imposed by, for example, scarcity of heating needs in the summer) and incremental capital cost (i.e., the cost of the enabling technology). Bubble size provides an estimation of market growth.

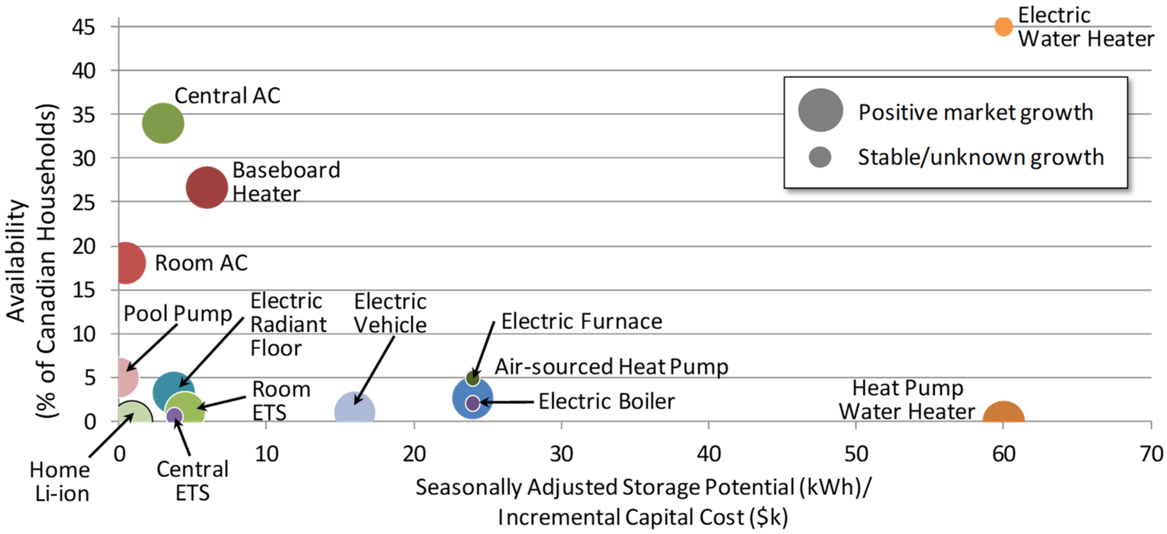


Figure 6: Potential of various residential end-use devices for storage

Electric water heaters (EWHs), specifically tank-types, have the highest overall potential for storage. From a per unit perspective, each can hold about 3-6 kWh of heat; the enabling load control technology can cost less than a few hundred dollars (CAD). (The cost of the tank itself is not included, as its primary role is to provide hot water to the end user and is required irrespective of whether its storage is kept for grid services.) Additionally, as almost half of Canadian households have EWHs, there is a huge pool of resources to draw from.

In the case of space heating and cooling, the storage potential that their respective devices can offer comes from the thermal capacitance of the houses. In newer houses, it can take several hours for indoor temperature to fall by 2-3°C in the absence of heating, all the while remaining in the comfort zone of occupants. In the above figure, both central air-conditioning units and baseboard heaters (among others) can take advantage of this storage; however, the former is limited by the seasonal (summer) need for air-conditioning and the latter is limited by the cost of outfitting many individual baseboards with smart thermostats.

In heating applications, energy storage can also be increased through electric thermal storage (ETS) devices, storing energy as heat within enclosed high temperature bricks. This solution offers storage at a fraction of a cost than that of comparable lithium-ion technologies but is available only during heating season.

Altogether, existing residential devices have the potential to provide 39 GW/85 GWh of storage in Canada [49].

3.5.2. DSM Potential

Historically, despite limited control technology, there has been some use of residential loads for flexibility, via demand response (DR). For example, some Canadian utilities have employed one-way communication devices such as pagers to deploy electric water heaters for peak shaving. In the Province of Quebec, where most heating is electric and makes up for a significant portion of peak loads, alternative rate schemes encourage homeowners to switch to other forms of heating during cold winter days. However, more complex DR applications capturing flexibility potential have been limited by the cost of deploying control infrastructure to these numerous small loads; up to now, it has been more cost effective to focus on large industrial customers.

With the advent of the smart grid, the two-way information and communications technology (ICT) it utilises, and the diffusion of low-cost internet-of-things (IoT) devices, it is now more feasible for utilities to aggregate the large populations of homogeneous loads that dominate the residential sector. With advanced (yet to be developed) controls and technology, new DSM strategies are possible. Realizing the load flexibility from the residential sector is seen as a new, alternative, low-cost solution for

- increasing the grid's capacity to integrate high penetrations of variable renewable energy such as wind and solar,
- reducing the need for fossil fuel generators (for load following and peaking), and
- lowering utility and rate-payer costs by improving asset utilization and deferring capital investments.

It is especially valuable for increasing the capabilities of local grids and distribution systems to incorporate more renewables, contributing to the establishment of clean, renewable, and resilient virtual power plants and microgrids.

3.5.3. Technology Pilots

Natural Resources Canada (NRCan) participates in a number of technology studies and pilots to evaluate the potential of residential loads to take part in advanced DSM strategies to serve the local distribution grid.

- During the winter of 2016-2017, NRCan collaborated with Hydro-Sherbrooke, a municipally-owned electric utility in the Province of Quebec, to demonstrate the demand response potential of smart thermostats to reduce peak demand [48]. A total of 92 smart thermostats controlling baseboard heaters in 11 houses were installed. Custom dynamic DR schedules were developed for each thermostat based on the initial schedule set by the occupant to allow the house to accumulate energy and redistribute it during the utility's peak period. It was found that applying setpoint modulation could reduce the average household's electric baseboard heating peak by 1.38 kW (60%) and 0.92 kW (54%) in the morning and afternoon mid-peak, respectively, without affecting the participant comfort. [50]

- In December 2018, NRCan began evaluating the DR potential of 400 EWH tanks equipped with communicating (Wi-Fi) controllers as the testing department of a project funded under the Build in Canada Innovation Program. These controllers will be installed on existing EXHs in occupied houses and apartments. One of the objectives of the field tests conducted will be to assess the peak power consumption reduction potential of a community of water heaters under various on/off schedule scenarios. In addition, the ability to use advanced controls to shape the demand profile of a group of EWHs to match a specific pattern will be evaluated.

3.5.4. End-to-End System Implementations

Two major projects in Canada's Atlantic provinces have implemented end-to-end programs (including utility system operations, ICT, controllable loads, and customer engagement) using flexible loads to increase their system's capacity to balance wind energy generation.

- The PowerShift Atlantic demonstration project, conducted over five years and completed in 2015, was a joint project between four utilities and a local university to demonstrate the technical and economic suitability of using customer loads to offset the intermittency of region's wind generation. It incorporated ETSs, EWHs, refrigeration, air-conditioning, and water storage towers (totalling 17.3 MW of connected load) in a virtual power plant managed by third-party commercial and residential load aggregators. [51]
- In Prince Edward Island's City of Summerside, the municipally-owned electric utility began using flexible residential loads in its smart grid in 2013. With a peak load of 26 MW and a wind capacity of 21 MW, wind energy often exceeds local demand. To increase utilization of this energy and reduce overall GHG emissions (from heating), the utility implemented i) a utility-side program, *MyPowerNet*, to link customer loads with the utility scheduling and control systems through a fibre optic network and ii) a client-side program, *Heat for Less Now*, to encourage uptake of ETSs and EWHs through rate incentives. Under this program, the utility reduced exports of excess wind energy by 17%. [52]

3.5.5. Future Outlook

The electric grid will be critical to future deep decarbonisation efforts; in addition to the role the grid presently serves, it will be required to distribute clean and renewable energy to new loads formerly supplied by fossil fuels. To make this future technically and economically feasible, this evolution will have to depend on loads playing a greater role – that is, they will have to be an active contributor to grid operations.

In the meantime, numerous short- and medium-term disruptors will influence how residential loads will contribute to the grid. Just to name two:

- Heat pumps are emerging as an alternative solution to resistance heating and may be a solution to replace natural gas furnaces. However, they still have significant peak loads during the coldest days of winter that must be mitigated; integrated phase change thermal storage is being investigated as a solution.
- Managing thousands of loads to provide advanced grid services while maintaining user comfort is a challenge for current control algorithms. Artificial intelligence, with its ability to handle large data sets, may be the best solution to achieve advance DSM control while considering individual user preferences.

In summary, the advanced load management of smart and connected devices will be key to achieving clean electric grids. They have significant, inexpensive potential that can be captured for grid services (e.g., load following, ramping, regulation, peak shaving) that will better allow utilities to integrate high penetrations of renewable power generation and cheaply meet future load growth.

3.6. Research development and demonstration examples

Power system operation will require radically new approaches for real time control that can accommodate the coordinated operation of millions of devices, of various technologies, at many different scales and voltage levels. To secure production capacity adequacy and reliability of a power system with high variable generation penetration an effective instrument is needed for its long-term design and optimization based on real characteristics.

A large number of research development and demonstration initiatives are and have been addressing these and other flexibility aspects in the recent years. Depending upon the time horizon and the scope, the ambitions may vary from rather evolutionary with minor changes of the system's architecture to very radical approaches, attempting to redesign the overall system architecture and autonomous grid areas. In this section a few of these projects have been highlighted.

The EcoGrid EU project (2011-2015) worked on the development and testing of new market concept allowing to improve the balancing mechanisms by introducing a 5 minutes real-time price response to provide additional balancing power from smaller customers directly to the Transmission System Operators [53].

The concept developed by the Cell Project looked at dividing the power system into virtual fully autonomous grid areas in terms of control, so-called cells. The cell concept could be realized through the development and implementation of an advanced monitoring and control system capable of monitoring the state of the cell and – in extreme situations – taking control of its individual units such as circuit breakers, transformers, wind turbines and CHP plants [54]. Division of the grid into semi-autonomous units is studied by the Fractal Grid project [55] and the C/sells project [56].

The web-of-cells approach has also been utilised in the ELECTRA Integrated Research Programme on Smart Grids (ELECTRA IRP), which addresses the issue of deployment of RES connected to the network at all voltage levels as well as establishes and validates proofs of concepts that utilize flexibility from across traditional boundaries in a holistic manner [57].

Currently, both day-ahead and intra-day markets are performed based on separated forecasts of energy needs, system congestions, and system contingencies, among others. Obviously, a better approach would be to perform all these forecasts in an integrated and unified manner by web-of-cell concept proposed in ELECTRA IRP. This methodology would allow network/cell operators to achieve optimal reliability and decision-making under uncertain dynamic conditions. The Web-of-Cells architecture keeps an idea that all system balancing products, which are needed to operate the power system are procured in a marketplace. The market for balancing and voltage control products is considered to be transparent if market transparency is achieved horizontally and vertically [58], [59].

Horizontal transparency is achieved in the market for balancing and voltage control products when the same level market actors (such as various types of electricity generators or system operators) exchange all relevant ex-ante and ex-post data and information among themselves timely for the efficient decision making, as illustrated in Figure 7.

Market design elements

General elements	Balance planning elements	Product provision elements	Imbalance settlement elements
-Bid Time Unit -Publication of Cell information	-Zonal vs. nodal responsibility -Balance obligation -Balancing scheme -Net vs. separate positions -Notification of energy schedules -Initial gate closure time	-Procurement scheme -Pricing mechanisms -Cascading procurement -Remuneration scheme -Activation scheme -Timing of market for balancing and voltage control products	-Imbalance settlement period -Types of imbalances -Imbalance pricing mechanisms -Imbalance price -Method for determination of imbalance price -Allocation of costs -Penalty for non-delivery -Timing of settlements

Market Design for balancing and voltage control products

Web-of-Cells architecture

Figure 7 Market design with the Web-of cells architecture, [57], [58]

The possibility to exchange and trade electricity at small scale within local communities is sometimes suggested as a possible route for integrating large amounts of distributed energy resources in a cost-effective way. The potential benefits identified in such cases should be weighed against the potentially increased transaction costs associated with small-scale transactions, and the increased operational costs for operating small market platforms.

Some local energy markets are, in similarity with many current wholesale electricity markets, based on centralized auctions for trading energy. At the Chalmers university campus in Gothenburg, Sweden, the Fossil Free Energy District (FED) project is demonstrating one such local energy market [60].

The FED energy market is designed to unlock the available flexibility potential from local resources. It does so by combining three different energy carriers (electricity, district heating and district cooling) in a single market that matches supply and demand frequently, just before delivery. A flexible bid structure makes it possible for market participants to represent complex dependency structures across energy carriers or over time. For example, a consumer who can use either electrical heat pumps or district heating for its heating needs, can represent this flexibility in their bids and thereby easily switch between the two energy carriers based on current market conditions.

The frequent updating and close to real-time market clearing help to facilitate the integration of small-scale, weather-dependent distributed energy resources. The FED market also includes detailed network models for all three energy carriers. This means that the market clearing functionality helps prevent network problems by clearing the market in a way that is compatible with the underlying networks.

An alternative to auction-based local electricity markets is a more decentralized peer-to-peer trading format. Peer-to-peer electricity markets based on blockchain technology has received a considerable amount of interest in recent years, with the Brooklyn Microgrid in New York as an example [61]. The peer-to-peer blockchain structure enables decentralized transactions without the involvement of a central intermediary. This may have benefits from an information security and resilience perspective.

Local electricity markets can also be oriented towards providing a platform where system operators, including DSOs, can procure balancing services from local distributed resources and demand response aggregators. One such example is the FLETCH concept [62], developed as part of the iPower platform in Denmark [63]. The concept is based on a flexibility clearinghouse that streamlines the business interactions between DSOs and aggregators in order to keep transaction costs as low as possible. With this market structure, DSOs submit requests for services that aggregators can bid for. By standardizing the flexibility services and bidding format, the clearinghouse concept aims at reducing transaction costs and thereby making market-based flexibility solutions a competitive alternative to more traditional grid infrastructure investments.

The project From micro to Mega-GRID (m2M-GRID) works on the development of solutions related to: the enhancement of distribution grid planning; control functions for effective coordination with distribution grids; and a toolbox to exploit the potential flexibility of micro-grids [64]. Within the m2M-GRID project, the interactions between commercial micro-grids and an upper market framework are studied. One aspect is related to how microgrids can interact with the upper market layer to provide different system services to DSOs and TSOs, both interaction locally (local markets and local communities) and at the wholesale level (intra-day and ancillary services markets). The project will work on developing a definition of a local market for energy and flexibility trading within micro-grids, as well as between micro-grids and with overlaying markets. Such market is intended to be aligned with the wholesale markets, but with the possibility to have another market time granularity, time horizon, or structure [65].

A new marketplace capable of exploiting decentralised flexibility is being developed by the Norwegian energy company Agder Energi and the Power Exchange Nord Pool through the recently established subsidiary NODES [66]. The intention is that this new marketplace, placing a value on flexibility, will bridge the gap between current wholesale power markets and local flexibility markets. The proof of concept has been demonstrated, and the intention is to utilise entities at different levels of the power system to provide and utilise flexibility services through a transparent marketplace open to all potential market participants, illustrated in Figure 8. Using available flexibility is an alternative to grid investments and creates opportunities for customers providing new services and enables greater integration of renewable energy.

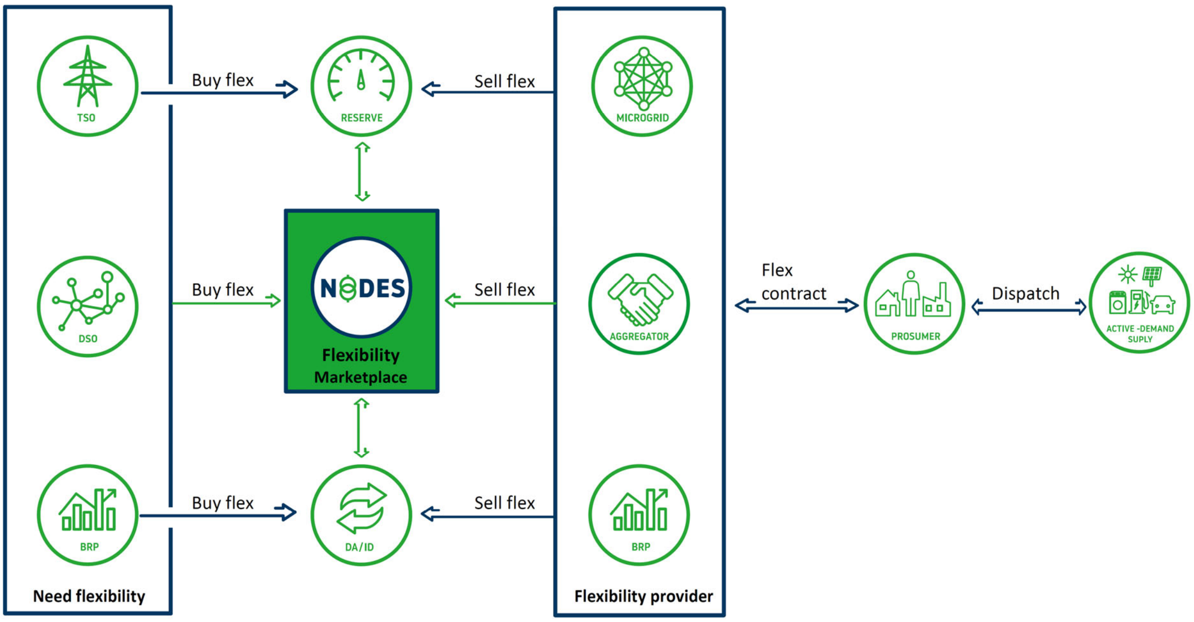


Figure 8 NODES flexibility marketplace concept, [66]

The EU-SysFlex project (Pan-European system with an efficient coordinated use of flexibilities for the integration of a large share of RES), [67], works on identifying a mix of flexibility and system services to support the secure and resilient operation of the power system.

The OSMOSE project (Optimal System-Mix Of flexibility Solutions for European electricity), [68], is an initiative of six TSOs coordinated by RTE. It focuses on the four topics, power transmission technologies, storage technologies and control tools for enhanced transmission grid flexibility, as well as improved energy market efficiency, in a context of high shares of RES. The project aims to define the conditions for an optimal mix of flexibility.

The integration of rapidly growing volumes of intermittent non-dispatchable (mainly wind and solar) Renewable Energy Sources (RES) into the traditional power system will massively increase the need for flexibility, not only to balance offer-demand in energy markets (A in Figure 9), but also to provide system services (B) and allow the dynamic control of grid flows (C). As various sources of flexibility (listed in Figure 9) emerge to replace the declining availability or closure of flexible thermal plants, the challenge for stakeholders in a pan-European electricity system is to establish competitive markets and regulatory frameworks that will enable affordable, reliable and sustainable development of flexibility assets by market players in coordination with regulated players. Achieving this objective will be a major challenge, because the underlying power system is changing dramatically. The penetration of RES renders obsolete many of the basic design assumptions underpinning current power systems (for example on the economic side through the near zero marginal cost of production of RES); and revolutionises system dynamics, as RES generation is connected via power electronics.

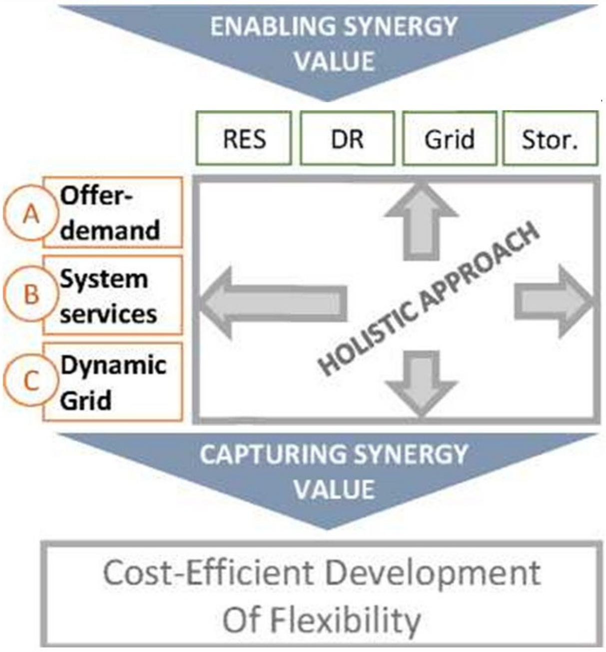


Figure 9 OSMOSE project approach

Attempting to match flexibility sources and flexibility needs within traditional organisational “silos”, as illustrated in Figure 9 would likely lead to considerable over investment in each silo, in comparison with more innovative solutions that would aim to capture synergies across and between silos. More precisely:

- for a given technology, the scope of application should not be restricted, e.g. smartly located and dispatched storage devices can support not only both offer-demand and system services, but also the dynamic control of grid flows in order to avoid congestions;

- for a given application, all technologies should compete on a level playing field, e.g. managing congestions using only grid devices (topology changes, phase-shift transformers, etc.) would waste the potential of flexibility from RES generation, demand response (DR) and storage;
- and for a given flexibility application, flexibility sources should compete independent on their country location (cross-border market integration).

The OSMOSE project aims to address, through a holistic approach, the identification and development of the optimal mix of flexibilities to enable the Energy Transition. The purpose is to consider the power system as a whole, embracing the necessary flexibility sources and identifying the techno- economic potential of technologies, regardless of traditional silos, in order to capture synergies and make the Energy Transition as affordable as possible.

This project will contribute to this purpose:

- by increasing the techno-economic maturity and scalability of flexibility solutions enabling “silo-breaking synergies";
- by forecasting the economically optimal mix of flexibilities for the pan-European power system, taking into account these synergies, for the maximum social welfare;

The MIGRATE project (Massive InteGRATion of power Electronic devices) is seeking to devise a grid-forming solution for 100% power-electronic grids (wind and solar), [69].

Once renewables reach a certain penetration share, conventional power plants inertia is no longer sufficient; large imbalances generate unauthorized frequency changes. Synthetic inertia (achieved for example by renewables) may help in a certain extent, by providing a power boost, which slows down the frequency drops.

However, above a certain share of renewables, synthetic inertia becomes no longer sufficient, as the rate of change of frequency turns out to be too high to be compensated by a power boost, which takes 100 ms to kick in. The situation gets even more dramatic in a system without any rotating machines at all, as there is no more any frequency conductor. Nevertheless, MIGRATE has shown that two options could be considered for addressing these frequency/stability challenges:

- Guaranteed rate of synchronous compensators running on no load.
- Grid-forming, where certain energy sources (renewables, batteries) will have to set the frequency and minimise frequency changes on the grid.

The arbitrage between both options largely depends on relative costs, which may evolve in the next decades. An additional key finding of MIGRATE is that stability (in both options) is very sensitive to the geographical siting of these units.

In Europe, there is a sharp increase in reserve needs for coping with the variability introduced by a steadily increasing RES share in the generation. The big challenge is to extend the possibility of providing Ancillary Services (AS), (frequency and voltage control, congestion management, etc.) to entities connected to the distribution network. The legislative package proposed by the European Commission in November 2016, nicknamed the Clean Energy Package, assigns a role to DSOs for local congestion management but not for balancing, whose management would remain in the hands of the TSOs [70]. However, such a sharp decoupling risks to lead to inefficient system operation.

All these issues are addressed by the SmartNet European research project [71], under technical and administrative management by RSE [72], which aims at comparing different TSO-DSO interaction schemes and different real-time market architectures with the goal of finding out which would deliver the best compromise between costs and benefits for the system. The objective is to develop an *ad hoc* simulation platform which models all three layers (physical network, market and ICT), analysing three national cases (Italy, Denmark, Spain). Subsequently, this simulation platform will be scaled to a full replica lab, where the performance of real controller devices will be tested.

The consortium, under technical and administrative management by RSE, consists of 22 partners from 9 European Countries, including TSOs (Energinet.dk, TERNA), DSO (ENDESA, SE, Edyna), manufacturers (SELTA, SIEMENS), and telecommunication companies (VODAFONE).

SmartNet analyses five different coordination schemes between TSO and DSO and different architectures for the real-time ancillary services markets with reference to three countries: Italy, Denmark and Spain. For each country, the model needed to perform significant simulations encompasses nodal representation of the transmission network and of the distribution networks (some of them represented in detail till medium voltage, some others in a more synthetic way), detailed representation of the different resources providing bids for system flexibility (both connected to transmission and distribution), detailed representation of the aggregation process and of the real-time ancillary services market.

SmartNet considers five TSO-DSO coordination schemes (CS) characterized by different roles and market architectures:

- **centralized AS market model (CS A):** TSO contracts services directly from DER. No congestion management is carried out for distribution grids;
- **local AS market model (CS B):** DSO manages a local congestion market. Unused resources are transferred to the AS market managed by TSO (procuring balancing and congestion management);
- **shared balancing Responsibility Model (CS C):** TSO transfers to DSO balancing responsibility for distribution grid. DSO manages a local congestion and balancing market using local DER;
- **common TSO-DSO AS Market Model (CS D):** TSO and DSO manage together a common market (balancing and congestion management) for the whole system;
- **integrated Flexibility Market Model (CS E):** TSOs, DSOs and commercial market parties contract DER in a common flexibility market (raising regulatory problems: not implemented in simulation).

In order to compare CS performance, SmartNet has developed a challenging simulation platform, modelling in detail T&D networks and ancillary services markets and implementing a very detailed dataset of generators and loads. Simulations are carried out on midterm scenarios (time horizon 2030) for Spain, Denmark and Italy to identify the best TSO-DSO coordination scheme for each country.

The same platform is also implemented in a laboratory in order to test real network equipment on the developed simulation scenarios (*hardware-in-the-loop*).

TSO-DSO coordination schemes are compared using a cost-benefit analysis with the following indicators:

- cost of mFRR (manual Frequency Restoration Reserve) purchased in AS market for balancing and congestion management;
- cost of aFRR (automatic Frequency Restoration Reserve) to cope with residual system imbalance not solved by mFRR because of simplified system representation, forecasting errors, network losses;
- ICT deployment costs.

Two additional non-monetized factors are monitored:

- amount of CO_2 emissions;

- unwanted measures (e.g. load shedding) activated in case of congestion still unsolved or unpredicted after AS market clearing. This creates further imbalance which is solved by aFRR.

A cash flow analysis is also carried out to assess revenue opportunities for the different market subjects.

The diagrams in Figure 10 synthesize the simulation results obtained from the Italian scenario.

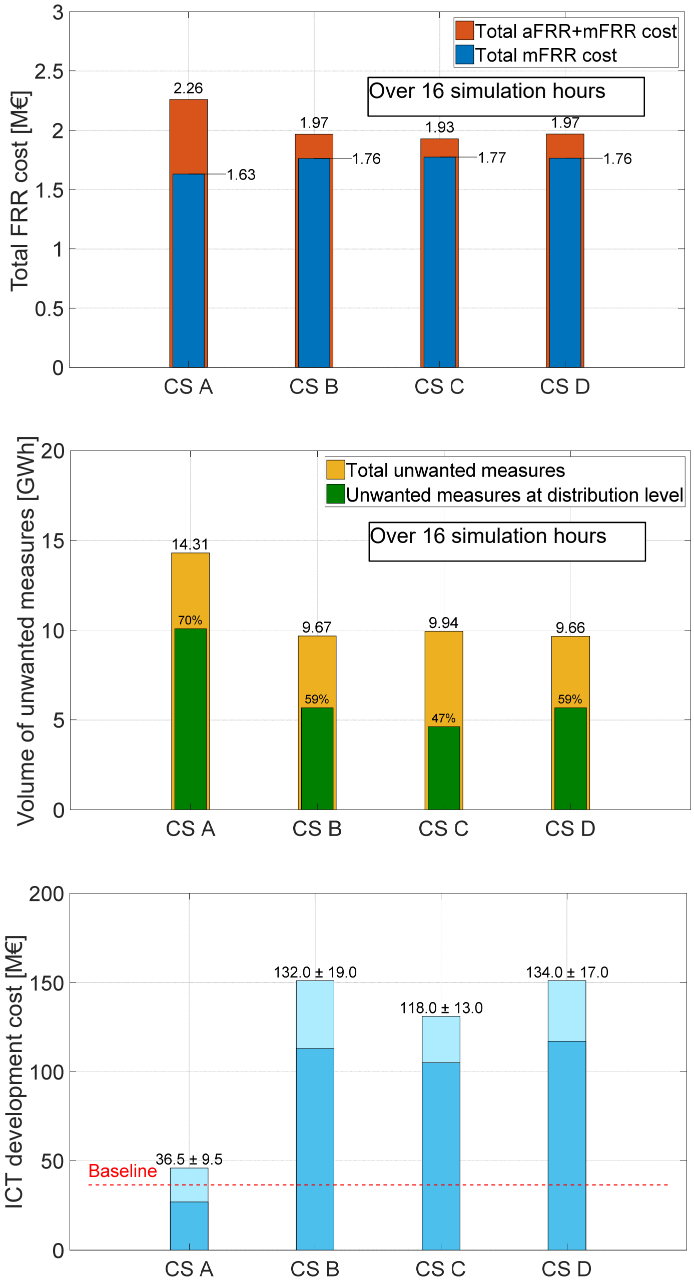


Figure 10 Italian scenario simulation results

The diagrams in Figure 10 allow the following conclusions to be drawn:

1. CS A performs worse than all other coordination schemes: disregarding congestion in distribution network brings to buy less mFRR but higher amount of more expensive aFRR. Unwanted measures are also much higher for CS A.
2. CS B and CS D perform equivalently: due to radial topology, congestion in distribution networks must be managed within the portion downstream the bottleneck. This generates an imbalance which can only be solved by the remaining part of the system.

This results in splitting the overall market into two sections where prices are formed independently.

3. CS C, even if much trickier to implement, performs well because the fragmentation of the AS market in several sections prevents to spread over the whole system high bid prices of some resources in distribution.
4. ICT costs are lower for CS A. As they are single-payment costs, their influence on the system expenses can be assumed negligible with respect to FRR costs (shown in the above diagrams aggregated over 16 simulation hours).

The SmartNet project also includes three physical pilots for testing specific technological solutions:

- technical feasibility of key communication processes (monitoring of generators in distribution networks while enabling them to participate to frequency and voltage regulation): Italian Pilot
- capability of flexible demand to provide ancillary services for the system:
  - thermal inertia of indoor swimming pools: Danish Pilot,
  - distributed storage of base stations for telecommunication: Spanish Pilot.

4. Conclusions & discussion

Power system flexibility relate to the ability of the power system to manage changes. However, flexibility is not a not a unified term and is lacking a commonly accepted definition. Several definitions of flexibility have been suggested, some of which restrict the definition of flexibility to relate to changes in supply and demand while others do not put this limitation.

The flexibility term is used as an umbrella covering various needs and aspects in the power system. This situation makes it highly complex to discuss flexibility in the power system and craves for differentiation to enhance clarity.

In this report, the solution has been to differentiate the flexibility term on needs, and to categorise flexibility needs in four categories:

- **Flexibility for Power:**
  Need Description: Short term equilibrium between power supply and power demand, a system wide requirement for maintaining the frequency stability.
  Main Rationale: Increased amount of intermittent, weather dependent, power supply in the generation mix.
  Activation Timescale: Fractions of a second up to an hour.
- **Flexibility for Energy:**
  Need Description: Medium to long term equilibrium between energy supply and energy demand, a system wide requirement for demand scenarios over time.
  Main Rationale: Decreased amount of fuel storage-based energy supply in the generation mix.
  Activation Timescale: Hours to several years.
- **Flexibility for Transfer Capacity:**
  Need Description: Short to medium term ability to transfer power between supply and demand, where local or regional limitations may cause bottlenecks resulting in congestion costs.
  Main Rationale: Increased utilisation levels, with increased peak demands and increased peak supply.
  Activation Timescale: Minutes to several hours.
- **Flexibility for Voltage:**
  Need Description: Short term ability to keep the bus voltages within predefined limits, a local and regional requirement.
  Main Rationale: Increased amount of distributed power generation in the distribution systems, resulting in bi-directional power flows and increased variance of operating scenarios.
  Activation Timescale: Seconds to tens of minutes.

Here, flexibility needs are considered from over-all system perspectives (stability, frequency and energy supply) and from more local perspectives (transfer capacities, voltage and power quality). With flexibility support considered for both operation and planning of the power system, it is required in a timescale from fractions of a second (e.g. stability and frequency support) to minutes and hours (e.g. thermal loadings and generation dispatch) to months and years (e.g. planning for seasonal adequacy and planning of new investments).

The categorisation presented in this report, supports an increased understanding of the flexibility needs, to be able to identify and select the most suitable flexibility solutions.

Given a functional flexibility market, flexibility resources are able to compete against each other with their specific technical advantages and constraints.

Providing long-term flexibility (e.g. seasonal storage) is in general much more expensive than short-term flexibility. However, flexibility to support short-term needs may be provided at almost zero costs from installations intended to provide long-term flexibility.

Furthermore, sector-coupling analysis examining the flexibility needs of the whole energy sector paves the way to a coordinated use of existing cross-sectoral flexibility solutions which reduce the over-all need for investments.

Coordination between TSOs and DSOs is essential to ensure that flexibility resources in distribution networks remain available for balancing purposes without inducing unmanageable local congestions, which could jeopardize the local grid.

An optimal mix of flexibility resources can be obtained through a holistic approach considering technical, commercial and environmental aspects.

Given a long term stable and permissible regulatory framework, with an innovative and transparent market environment: properly designed systems for measurement, information and communication, monitoring, control and protection, can provide key solutions for flexibility which is increasing needed in the future power systems.

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