European Commission

Flexibility for Resilience

How can flexibility support power grids resilience?

ETIP SNET

European Technology and Innovation Platform Smart Networks for Energy Transition

ISGAN

INTERNATIONAL SMART GRID ACTION NETWORK

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Joint work of ISGAN Annex 6 and ETIP SNET WG1

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Insides from many of the ongoing projects provided highly relevant knowledge to the question of How flexibility can support power grid resilience.

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EXECUTIVE SUMMARY

As zero operational-cost variable Renewable Energy Sources are foreseen to dominate the future energy mix, the abundance of green electricity will allow the replacement of fossil fuels in sectors such as heating, cooling, industrial processes, and transport.
The intermittency of such energy resources implies significant systemic requirements for flexible solutions; thus, developments of the energy sector in general, and the power system in particular, instigate significant innovation activities in the fields of power system flexibility. Concurrently, complexities and interdependencies of system components and multitude of actors increase the risks of service failures and the complexity of production and grid planning, raising the demand for stronger and more agile resilience means and countermeasures.
In this white paper we discuss the item "How can flexibility support resilience?", considering the increased societal needs of a secure electricity supply.

Power system resilience reflects the impact of severe events and is an overarching concept, covering the whole spectrum of the power system from design and investment decisions to planning, operations, maintenance and asset management functions. As such, the concept of power system resilience applies to the planning time frame that looks to build resilience into the future network, as well as the operational time frame, in which security is managed by optimizing the inherent resilience of the existing power system.

Flexibility concerns the power systems ability to manage changes, with flexibility features able to improve the resilience characteristics of the broader view system of systems, provided that they are integrated in grid planning, in defence plans, and properly evaluated in the energy market design. Flexibility capabilities need to be considered from the planning stage, using a holistic approach aimed at grids to be flexible and resilient by design. Flexibility resources can also facilitate the restoration process by exploiting distributed black start capabilities including sector-coupling, which adds a new dimension to the necessary interactions pattern between electrical TSOs and DSOs, with utilities from other sectors. Power system planning for the future grid must embrace a wide range of network and non-network options to create operational flexibility options, including more active demand management techniques and customer-sensitive smart load shedding procedures.
The next level of flexibility is seen as being fully deployed and utilized for operation and planning of the power system, being integrated in procedures for long-term planning as well as in tools for stability support. The integrated dependency of flexibility directly impacts the resiliency of the power system, thus flexibility solutions intended to provide resilience support must be reliable and secure to provide the trust required for operation and planning.

Many of the worldwide ongoing initiatives can provide highly relevant knowledge to the question of How can flexibility support resilience? Indeed, they show the relevance and the potential values to be unlocked, with potentially some low hanging fruits to start with.
Some of the examined areas include:

- System Integrity Protection Schemes
- System Technical Performance
- Alternative Grid Development

The economic value provided by large scale flexibility solutions can increase the benefit of maintaining high levels of resilience and thus provide incentives for resilience-enhancing investments. Additionally, cyber security is an area with increased focus as part of the power system digitalisation. Finally, standardisation of solutions is important to increase the reliability & acceptance in order for large scale deployment of flexibility.

1. INTRODUCTION

ISGAN Annex 6 on *Power Transmission & Distribution Systems* is an international collaborative initiative, with the objective to establish a long-term vision for the development of the future sustainable power systems. **ETIP SNET WG 1** on *Reliable, economic, and efficient energy system* is a European Commission initiative, addressing business and technology trends contributing to the overall energy system optimisation at affordable investment and operation costs. Under the framework of a Memorandum of Understanding aimed at mutually benefitting of respective expertise, these two platforms have agreed on the collaborative effort to prepare this White Paper dedicated to address how flexibility can provide value for the resilience of the power system.

This collaboration started through a common workshop uniting experts from ISGAN Annex 6 & ETIP SNET WG1 into the Task Force on Flexibility for Resilience[1]. Presentations at the workshop provided multifaceted views which created a basis for further development of the content of this Paper, including contribution from the international work of CIGRE, the over-all System Operation and TSO perspectives, to the DSO and Local energy community perspectives. A large number of relevant projects and solutions were presented and discussed, with details from these and other initiatives included in the Appendix of this report.

As zero operational-cost variable Renewable Energy Sources (vRES), such as wind farms and photovoltaics, are foreseen to dominate the future energy mix, the abundance of green electricity will allow the replacement of fossil fuels in sectors such as heating, cooling, industrial processes, and transport. The intermittency and/or level of controllability of such RES implies the need for the system of large amount and different types of flexibility means; therefore, the development of the energy sector in general, and the power system in particular, have led to significant innovation activities in the fields of power system flexibility. At the same time, the complexity and interdependencies of system components and multitude of actors increase risks of service failures, thus raising needs of reliable and more flexible resilience means and countermeasures.

By analysing power system-related challenges and solutions, this white paper provides a consolidated view and input for **R&D activities and innovation projects on power system flexibility and resilience**, in particular on how to design and exploit flexibility sources and mechanisms also for increasing the resilience of the overall system; this includes technology, market and regulatory aspects of transmission and distribution systems, as well of the coupled energy sectors. The work is based on professional expertise and international experiences, contributing to the topic with different competences including: flexibility resources and tools, system operation, system planning, resilience assessment and cross-sectoral view.

How to read the document. The work has been prepared through collecting, integrating, and synthesizing information from innovation projects (see Appendix), surveys, workshops, and solutions-oriented discussions, with the goal of delivering key messages towards all power system actors and stakeholders.

[1] https://www.etip-snet.eu/isgan-annex-6-etip-snet-wg1-task-force-flexibility-resilience-workshop/ https://www.iea-isgan.org/isgan-annex-6-etip-snet-wg1-task-force-on-flexibility-for-resilience-workshop-june-1st-2021/

2. POWER SYSTEM TRANSFORMATION

This section, in a very concentrated way, highlights Flexibility[2] and Resilience aspects leading power system transformation[3] to establish a long-term vision for the development of the future sustainable power systems. Targeting high vRES penetration, Flexibility should be included for grid operation, and starts being considered at the investment planning stage. Flexibility can support grid Resilience contributing to the reliability measures within the perimeter of the electric power system.

2.1. Integrated systems and increased complexity

If planning of the power systems does not provide adequate levels and availability of flexibility resources, especially regarding contingencies (i.e. unforeseen, rapid changes of operational conditions), the existing resources may become insufficient to guarantee a stable operation and ensure the continuity of supply. The reinforcements and optimal utilisation of system resources are necessities to maintain the functionality of the increasingly complex and intertwined energy system ("system of systems"). Thus, the investment planning process is a first key step to ensure the adequacy of future electricity system, i.e. sufficient ability to accommodate the growth of variable generation from renewable energy sources and to cope with foreseeable contingencies.

For this aim, different sources of flexibility must be utilized, provided by the various equipment connected to the system. This requires an approach involving activities from the consumers and from actors in other energy systems, which can be utilised also to increase the resilience of power grids against a variety of future threats.

Generally, the electrical infrastructure is designed considering the possibility of a quick reaction to possible threats of various nature. The progressive electrification, as one of the directions adopted for decarbonisation of other sectors, carries with it even greater challenges for maintaining the stability and continuity of electricity supply. On the other hand, the activation of consumers as well as the pursuit of energy efficiency and optimization show that in the future market, the use of sources of flexibility will play a significant role in the management of the power system.

Furthermore, a high level of flexibility and system integration will not be possible without deep digitalization of all energy sectors. Consequently, data used in the operational processes are requiring proper management in the handling of big data. Here, artificial intelligence and machine learning techniques and algorithms will be able to provide significant value and support to the energy sector [4]. At the same time, the amount and the level of cyber threats increase due to the interconnections and interdependencies.

The increased complexities thus require a shift of the centre of gravity of trust:

- from trust in the reliability and appropriateness of established human procedures
- to trust in procedures created, activated, and executed by automatised systems.

The traditional way of addressing flexibility and resilience as separate areas is thus insufficient to cope with future developments. For the sake of clarity, commonly accepted definitions for flexibility and resilience are needed. In the following subsections, simplicity is proposed in both these regards.

2.2. Flexibility for resilience in integrated systems

Both Flexibility and Resilience have to be addressed: Flexibility for grid operation with high vRES penetration, starts being considered at the investment planning stage and Resilience, based on reliability, risk analysis, system interactions analysis, within the perimeter of the electric power system.

With a broader view, resilience can be improved also by exploiting the short-term flexibility means for operation, both within the power system as well as from sector coupling.

Building on previous works on flexibility and on resilience, the target is to assess how the new flexibility features can also improve the resilience characteristics of such larger system; relevant best practices and projects worldwide are then analysed and reported in Appendix.

Flexibility measures originating from sector coupling are particularly relevant since these are additional to those within the boundary of the power system. Extraordinary events may impact energy sectors differently, meaning that coupled sectors can support each other in case of severe contingencies.

Flexibility resources can also facilitate the restoration process after severe faults by exploiting black start capabilities in other sectors. This further adds a new dimension to the necessary interactions pattern between electrical TSOs and DSOs, with utilities from other sectors.

2.3. Defining Flexibility in the power system context

Flexibility of the power system concerns the power systems ability to manage changes, which can impact the preservation of a secure and reliable operation of the power system. Flexibility solutions provide support to the grid during normal operation, where the benefits provided by increased flexibility include decreasing of overall costs and the overcoming of challenges related to for example grid congestion. Flexibility needs span the timescales from sub-seconds to seasons and years, on local and over-all system levels, as illustrated in Figure 1.

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[2] Our previous work on flexibility: https://www.iea-isgan.org/wp-content/uploads/2019/03/ISGAN_DiscussionPaper_Flexibility_Needs_In_Future_Power_Systems_2019.pdf

[3] Our previous work on power system development trends: https://www.iea-isgan.org/wp-content/uploads/2020/05/ISGAN_DiscussionPaper_Annex6_microVsMEGA_2020.pdf

[4] E.Mataczyńska, C.Mataczyński, "The new era of technology in energy sector", Analiza IPE 2/2020, 2020

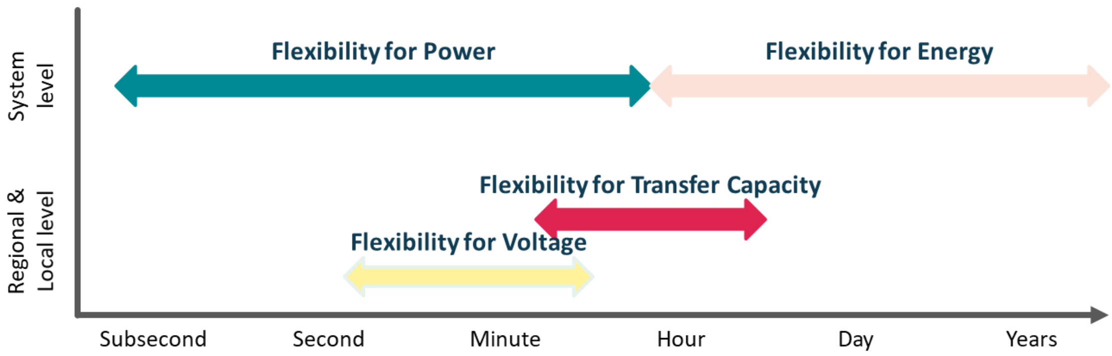

Figure 1 Flexibility needs from spatial and temporal perspective[5]

There are several definitions intending to describe the term flexibility, e.g.:

- *Flexibility of operation – the ability of a power system to respond to change in demand and supply – is a characteristic of all power systems. Flexibility is especially prized in twenty-first century power systems, with higher levels of grid-connected variable renewable energy: primarily, wind and solar* [6].
- *Flexibility – the ability of a system to respond to changes in demand and variable generation*[7] .
- *Flexibility expresses 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* [8].
- *Flexibility means 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)*[9].
- *Flexibility is defined as the modification of generation injection and/or consumption patterns, on an individual or aggregated level, often in reaction to an external signal, to provide a service within the energy system or maintain stable grid operation. The parameters used to characterise flexibility can include: the amount of power modulation, generation forecasts, the duration, the rate of change, the response time, and the location. The delivered service should be reliable and contribute to the security of the system)*[10].

Most presented definitions have specifics coming from different perspectives, as highlighted in[11], while the various needs in the power system and solutions are extremely broad. Therefore, a broad definition as proposed by[12] - relating to the general ability to manage changes - has a value in the sense of widening the understanding of the flexibility as a concept and preventing limited views on solutions.
Solutions providing flexibility become especially relevant with higher share of variable renewable energy sources. Flexibility solutions enable connected entities to support the grid as needed, utilizing the abilities of available grid elements.

A fundamental distinction can be made between flexibility provided by market participants and flexibility applied by network operators. In the context of market participants, flexibility refer to provisions given under the influence of external, mainly commercial, incentives. In the case of network operators, flexibility results from the obligation to ensure secure, adequate, and efficient planning and operation of the power system, and is related to security of supply and quality of service. Such flexibility can support system operators to maintain the expected level of performance if the network is under system constraints. Increasingly important is the operational flexibility, in other words, used in the day-to-day operation of the network[13].

The basic classification of flexibility, which results from the proposed regulations at the EU (EU 2019/944) level, is flexibility from the point of view of the power system and flexibility from the point of view of users. Flexibility from the point of view of the power system could be considered on two areas, namely: the technical area and users' behaviour area, Figure 2.

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[5] E. Hillberg et.al., "*Flexibility needs in the future power system*", ISGAN, 2019, DOI: 10.13140/RG.2.2.22580.71047
[6] Clean Energy Ministerial, "*Flexibility in 21st Century Power Systems*", NREL/TP-6A20-61721, 2015
[7] Bonneville Power Administration, Technology Innovation Project, "*Strategic and Flexible Transmission Planning*", TIP 256: EPRI P40.019, v.3.1, 2014
[8] International Energy Agency, "*Harnessing variable renewable - A Guide to the Balancing Challenges*"., Tech. rep.; 2011,
[9] Eurelectric, "*Flexibility and Aggregation: Requirements for their interaction in the market*", 2014
[10] CEDEC, EDSO, eurelectric, GEODEC, "*FLEXIBILITY IN THE ENERGY TRANSITION. A Toolbox for Electricity DSOs*", 2018
[11] CIGRE Working Group C5.27, "Short-term flexibility in power systems: drivers and solutions", TB 800, 2020
[12] E. Hillberg et.al., "*Flexibility needs in the future power system*", ISGAN, 2019, DOI: 10.13140/RG.2.2.22580.71047
[13] IRENA, "*Power system flexibility for the energy transition. Part II: IRENA flextool methodology*", ISBN: 978-92-9260-089-1, November 2018

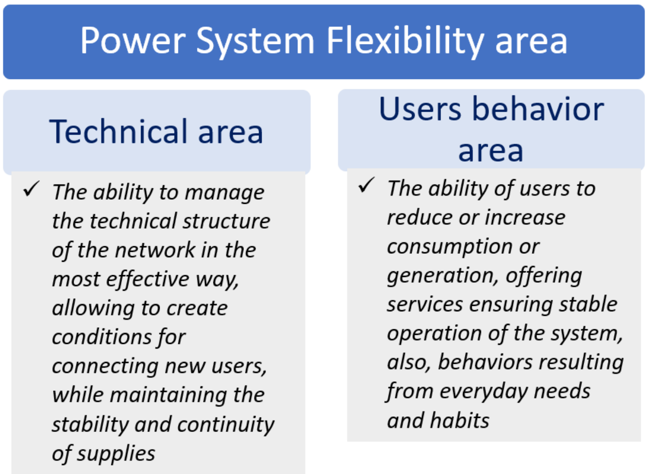


Figure 2 Flexibility areas from the power system point of view[14]

The technical area relates to the system's existing capabilities to deal with current problems. In other words, it is the ability to manage the existing technical structure of the network in the most effective way, allowing for the creation of conditions for connecting new users, while maintaining stability and continuity of supply.

Flexibility from the point of view of users is discussed further in section 4 – Flexibility and Societal Transformation.

2.4 Defining Resilience in the power system context

Resilience of the power system reflects the impact of severe events. It is a way of describing the power systems ability to deal with extraordinary disturbances, high-impact low-probability (HILP) events, or rapidly changing external conditions. Assessment of resilience include a system's ability to withstand an event, the rapid recovery from a disturbance, as well as its adaptability to prepare against future threats.

Some of the areas threatening the functionality of the power system relate to instability, cyber security, and climate change. The energy sector faces multiple threats from climate change, in particular from extreme weather events and increasing stress on water resources. Greater resilience to climate change impacts will be essential for the technical viability of the energy sector and its ability to cost-effectively meet the rising energy demands driven by global economic and population growth and electrification to decrease the carbon footprint of various sectors. Moreover, in the era of digitalization, cyber security is playing an increasingly important role and hacker attacks may have significant and extensive impact on the system. Other antagonistic threats to the power system involve e.g., ageing or damaging of physical assets, gathering of sensitive information, strategic investments, and control of critical delivery chains[15].

In this document, the focus lies on engineering resilience, although other considerations of resilience include both ecological and adaptive resilience[16], Figure 3.

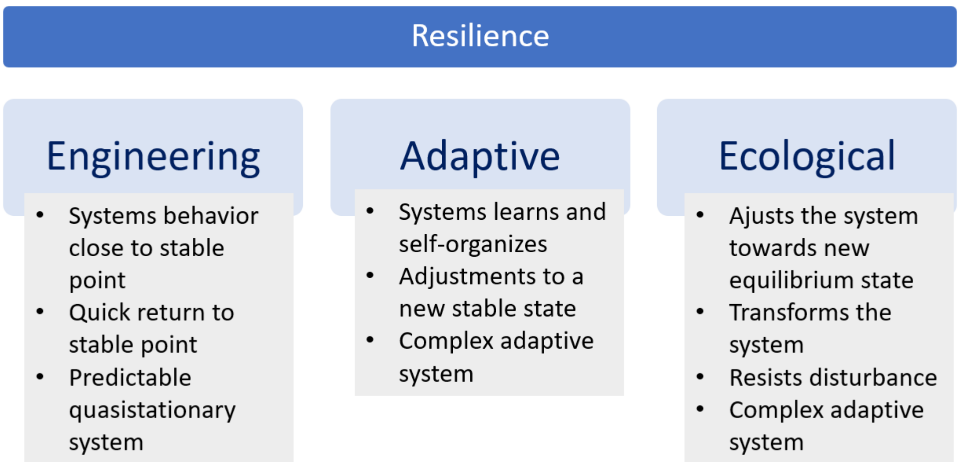


Figure 3 Overview of basic type of resilience.

Engineering resilience describes the ability of a system close to a stable point to quickly return to that point after a sudden event occurs. This means that engineering resilience focuses on the state of equilibrium that the system will return to when a sudden instability is resolved.

[14] E. Mataczyńska, "*Usługi elastyczności. Możliwości interpretacyjne zapisów pakietu Czysta Energia dla wszystkich Europejczyków*", Report IPE, 2020

[15] Svenska kraftnät, "*Open antagonistic threats to the electricity supply*" (in Swedish), November 2021

[16] BJ. Jesse, H. Heinrichs, & W. Kuckshinrichs, "*Adapting the theory of resilience to energy systems: a review and outlook*". Energ Sustain Soc 9, 2019, DOI:10.1186/S13705-019-0210-7

Engineering resilience usually focuses on performance and consistency and is used for description of systems made up of multiple components and interconnections that will be able to learn from or adapt to new situations specific to the event that caused the instability. Power system resilience is often understood from an engineering resilience perspective, with the power grids considered as critical infrastructure.

Ecological resilience focuses on a system's ability to absorb disruptions, including unpredictability and the capacity of a system to reach a new state of equilibrium.

Adaptive resilience focuses on a system's ability to adjust, learn, and re-organize, including unpredictability and the capacity of a system to reach an acceptable new steady state if the change is irreversible.

Resilience has been defined in many ways, consider, for example, the following definitions from engineering literature, policy directives, and the academic community:

- *Resilience is the ability of the system to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time and composite costs and risks*[17].
- *Resilience is the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events*[18].
- *Power system Resilience is the ability to limit the extent, severity and duration of system degradation following an extreme event*[19]
- *The resilience of the distribution system is based on three elements: prevention, recovery, and survivability. System recovery refers to the use of tools and techniques to quickly restore service to as many affected customers as practical. Survivability refers to the use of innovative technologies to aid consumers, communities, and institutions in continuing some level of normal function without complete access to the grid.*[20]
- *Resilience is the ability of a system (and its components) to adapt to changing conditions; and withstand and recover from disruptive events.* [21]
- *Infrastructure resilience is the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event.*[22]
- *Resilience is the ability to anticipate, prepare for, and adapt to changing climate conditions and withstand, respond to, and recover rapidly from disruptions.*[23]

The high level of details included in and surrounding several definitions of resilience, together with the fact that parts of the definitions involve relations to solutions to increase resilience, are preventing a common definition to form. Resilience metrics vary as well, being e.g., measures of (possible) impact or quantities required to keep impact at a certain level, see Figure 4. Therefore, the logic of a broad definition - relating solely to the impact of severe events – would simplify the understanding and the discussion on solutions providing increased resilience.

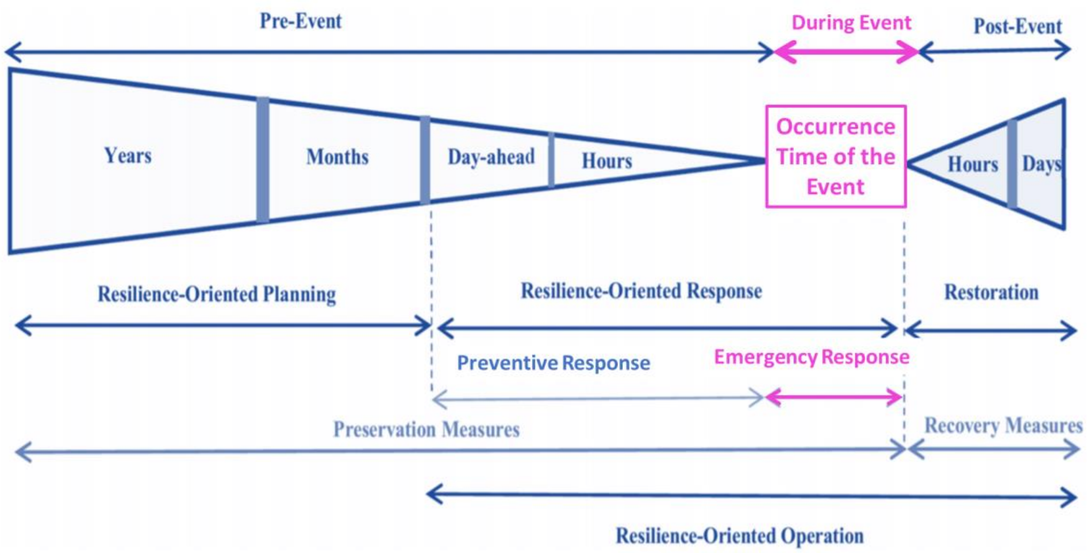


Figure 4 Resilience measures to consider different phases, with dedicated deployment before, during, and after an event[24]

A set of key actionable measures can be deployed before, during, and after an event, to achieve or enhance resilience. Such measures include

[17] Y. Y. Haime, "*On the Complex Definition of Risk: A Systems-Based Approach*", Risk Analysis, Volume 29, Issue12, 2009.
[18] National Research Council, "*Disaster Resilience: A National Imperative*", 2012, DOI:10.17226/13457
[19] CIGRE WG C4.47, "*Defining power system resilience*", ELECTRA no. 306, 2019
[20] Electric Power Research Institute, "*Enhancing Distribution Resiliency: Opportunities for Applying Innovative Technologies*", 2013
[21] S. Mishra, K. Anderson, B. Miller, K. Boyer, A. Warren, "*Microgrid Resilience: A holistic approach for assessing threats, identifying vulnerabilities, and designing corresponding mitigation strategies*", Applied Energy Volume 264, 2020,
[22] National Infrastructure Advisory Council, "*A framework for establishing critical infrastructure resilience goals: Final report and recommendations*", 2010
[23] B. Obama, "*Preparing the united states for the impacts of climate change*", Executive Order 13653, 2013
[24] M. Mahzarnia, M. Parsa Moghaddam, P.T. Baboli, P. Siano, "*A Review of the Measures to Enhance Power Systems Resilience*", IEEE Systems Journal. 10.1109/JSYST.2020.2965993, 2020

anticipation; preparation; absorption; sustainment of critical system operations; rapid recovery; and adaptation. [25]

Anticipation and preparation involve measures to be taken in advance, before any occurrence of an event. This may include scenario based mitigating strategies and plans for emergency actions.

Absorption relates to the system's ability to absorb/withstand the impact during an event, aiming for decreased or avoided consequences.

Sustainment of critical system operations and **rapid recovery** relate to processes during and after an event, to maintain the available operational capabilities and to rebuild the system to be able to return to normal operation.

Adaptation are measures taken after an event, where application of lessons learnt are basis to improve the system and increase its resilience to other events.

Resource adequacy vs resilience

Adequacy aims at identifying future missing assets for ensuring reliable service, so it is indeed a separate issue from resilience to extraordinary events, which in a sense could be seen as an extension of adequacy (in extreme conditions) when considering actions and options beyond building assets (generation or transmission); so a balanced position from this white paper perspective can be to evidence in our analysis the cases and situations where increased resilience can be reached simply through extra assets, in which case the solutions from adequacy studies are sufficient also for resilience. As well as, the resource adequacy construct is transitioning towards flexible capacity requirements, i.e., long-term planning for flexibility. Of course, there are many more situations/risks which cannot be solved only by extra assets, these are more in focus of this paper.

[25] CIGRE WG C4.47, "*Defining power system resilience*", ELECTRA no. 306, 2019

3. HOW CAN FLEXIBILITY SUPPORT POWER GRID RESILIENCE

Flexibility basically relates to solutions with the objective to support the system in daily operation (during normal, or close to normal, operation), while resilience on the other hand is a measure of impact of extraordinary events (i.e. far from normal operation). This section provides details on the understanding of extraordinary events, resilience measures, and developments of the flexibility concept.

3.1 Resilience against extraordinary events

A common understanding and view of power system resilience is an important step toward the design of solutions to provide increased resilience. Equally important is the identification and understanding of threats in terms of frequency and impact of extraordinary events. It is worth mentioning that some threats might be identified through the search for warning signs in operation and planning, while other threats are unpredictable. Furthermore, developments in technological solutions may raise some side-effects resulting in new threats which need to be identified, see Figure 5.
Extraordinary events threatening the power system may be categorized based on their main cause and impact on the power system. Three main type of event categories may be distinguished: [26]
Power system-initiated events: where main cause originate from technical or operational failures inside the power system (e.g. component malfunction, faulty protective actions, operator errors, or overloading), typically evolving in a cascaded manner.
Relatively short duration is categorizing this type of events, since, if no major mechanical breakdown occurs, restoration mainly relates to the re-energization and re-synchronisation of power system components. Power system-initiated events may in many cases be prevented by increased system reliability in the design phase, including more backup components, redundancy schemes, and parallel connections.
External events: caused by deliberate or accidental actions by a third party, e.g., cyber and physical attacks.
Cyber-attacks are relatively new and are gaining in importance with the widespread digitization with big data, new technological possibilities for communication, and remote access to many devices. Cyber-attacks resulting in severe blackouts are rare, but several cyber incidents have occurred in the last years.
Natural hazard events: caused mainly by factors related to the environment, such as adverse weather (extreme wind, icing etc.), natural disasters (e.g., forest fires, landslides, earthquakes, or volcanic eruptions) or space weather (incl. geomagnetically induced currents as result of severe geomagnetic storms).
Extensive tripping and destruction of power system components are often characterizing natural hazard events. Such direct impact on the mechanical structures of the power system, as well as on other infrastructures, may significantly delay the restoration process prolonging the duration of the blackout. Natural hazard events may in many cases be prevented by increased **mechanical dimensioning** of power system components and structures and locating them in a less exposed environment.

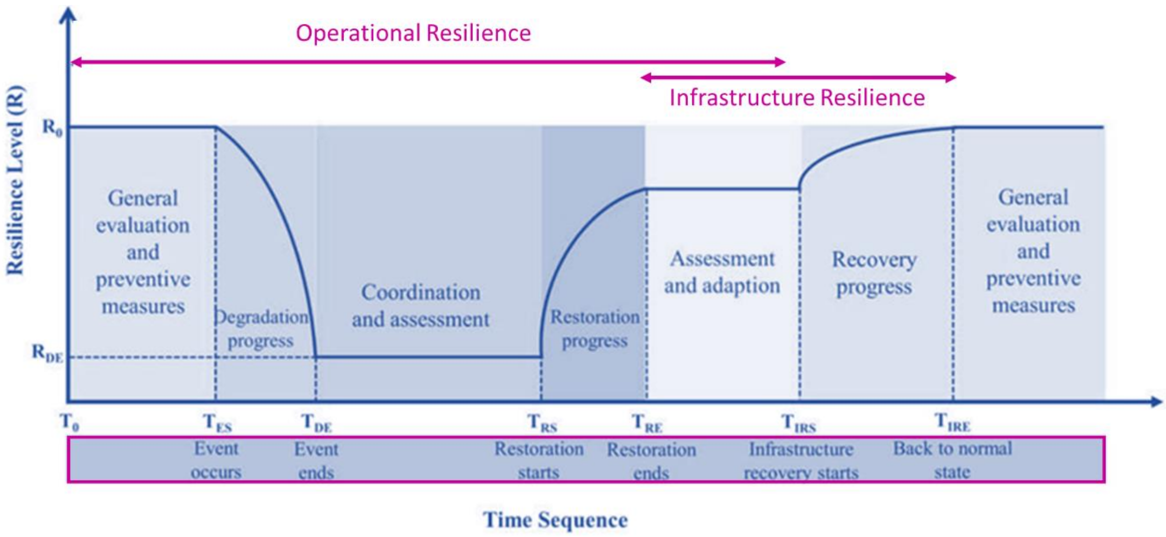


Figure 5: Curve for different resilience states of power distribution systems, from [27].

Overall, the resilience of power grids can be assessed on two levels: at component level and at system level. Research based on the analysis of individual elements and their resilience is important from the point of view of the proper design of the network. However, the power system is made up of many parts whose interactions are complex and difficult to calculate. In order to capture both the physical and cyber interdependencies of these components, it makes sense to study system-wide system-level resilience rather than analysing the resilience of individual components.

[26] E. Hillberg, "*Perception, Prediction & Prevention of Extraordinary Events in the Power System*", Doctoral thesis, NTNU, 2016
[27] S. Afzal, H. Mokhlis, H. A. Illias, N. N. Mansor, H. Shareef, "*State-of-the-art review on power system resilience and assessment techniques*", IET Generation, Transmission & Distribution, 2021, ISSN 1751-8687.

3.2 Resilience metrics and quantification

Various commendable efforts have been made to explain power system resilience in recent years, e.g. [27], [28], [29], [30], [31], [32]. In this section, several characteristics of resilience are presented, and quantitative resilience metrics are explained, Figure 6.
As resilience is a general concept for any infrastructure, literature on resilience emphasizes the **concept of 'community resilience'** to highlight the fact that different types of infrastructures are interdependent [32], including:

1. Electric power delivery, with subsystems distribution, transmission, and generation;
2. Telecommunications, with subsystems of cable, cellular, Internet, landlines, and media;
3. Transportation, with subsystems air travel, roadways, fuelling: gas stations, mass transit, rail, and water and port facilities;
4. Utilities, with subsystems water supply, sewage treatment, sanitation, oil delivery and natural gas delivery;
5. Building support, with subsystems heating, ventilation, air conditioning, elevators, security and plumbing;
6. Business, with subsystems computer systems, hotels, insurance, gaming, manufacturing, marine-maritime, mines, restaurants and retail;
7. Emergency Services, with subsystems emergency phone line, ambulance, fire, police and shelters;
8. Financial systems, with subsystems ATM, banks, credit cards and stock exchange;
9. Food supply, with subsystems distribution, storage, preparation, and production;
10. Government, with subsystems of offices and services;
11. Health care, with subsystems of hospitals and public health.

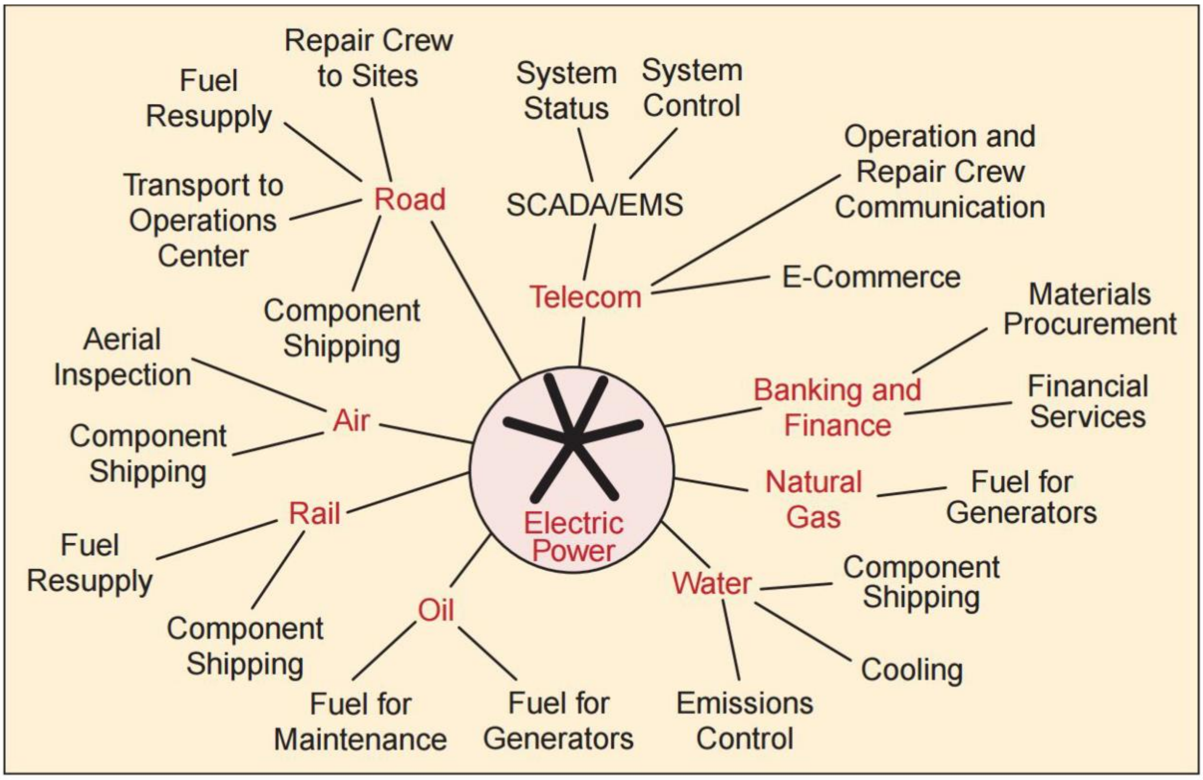


Figure 6: Electric power infrastructure dependencies, from [33]

Resilience metrics are tools to measure levels of resilience of the power system. Until now, there have been no standard resilience metrics, nor are there standard methods to evaluate them. Although several resilience metrics have been proposed, it is still an ongoing discussion on how to establish a standardized set of resilience metrics, especially when there is an opportunity of using flexibility resources to support grid resilience. Appropriate assessment of the power system resilience level leads to effective and rational strategies, e.g. to introduce

[28] E. Vugrin, A. Castillo, and C. Silva-Monroy, "*Resilience metrics for the electric power system: A performance-based approach*", Sandia Nat. Laboratories, Albuquerque, NM, USA, Tech. Rep. SAND2017-1493, 2017
[29] N. Bhusal, M. Abdelmalak, MD. Kamruzzaman, and M. Benidris, "*Power System Resilience: Current Practices, Challenges, and Future Directions*", IEEE POWER & ENERGY SOCIETY SECTION, , 2020
[30] A. Gholami, T. Shekari, M. H. Amirioun, F. Aminifar, M. H. Amini, and A. Sargolzaei, "*Toward a consensus on the definition and taxonomy of power system resilience*", IEEE Access, vol. 6, pp. 32035–32053, 2018
[31] R. Habibollah, V. Vahid, M. Kamyar, "*Power Systems Resilience Metrics: A Comprehensive Review of Challenges and Outlook*", MDPI, 20 November 2020
[32] Y. Tan, "*Power System Resilience under Natural Disasters*", Doctoral thesis, University of Washington, 2018
[33] Y. Tan, "Power System Resilience under Natural Disasters", Doctoral thesis, University of Washington, 2018

advanced control techniques, to improve recovery processes, or to update assumptions in grid planning. It is proposed [34], [35], [36] that resilience metrics, and methodologies for determining such metrics, should reflect a number of attributes, such as:

- Consistency with the adopted definition of resilience
- Distinguishing from reliability metrics through the basis of extraordinary events
- Distinguishing between operational and infrastructure resilience
- Supporting policymaking
- Support decision-making in planning and operation
- Providing quantitative or qualitative representations
- Utilising data that can be obtained, transparent, replicable, and well documented
- Basing on risk, considering threats, vulnerabilities, and consequences
- Accounting for uncertainties inherent in the assessment.
- Quantifying consequences in various measures, e.g. related to energy delivery or population/consumers without power
- Easiness to apply and analyse to take appropriate action
- Easiness to adapt to progress taking place in the environment
- Supporting planning for and responding to extraordinary events
- Providing effective, precise, and consistent means to communicate resilience issues
- Informing of the baseline assessments which quantify the current state of resilience
- Supporting the response to emergency and recovery activities
- Supporting the creation of development plans to improve resilience to future hazards

Resilience metrics may be divided in two categories: Attributes-based metrics, providing information on what makes the system more or less resilient. Performance-based metrics providing information on how resilient the system is, based on the interpretation of quantitative data of specific disturbances. Furthermore, performance-based metrics could be divided into a number of sub-groups, including the following type of resilience metrics: [36]

- **Power**: levels of power or energy, such as production/load mismatch, generation capacity, unsupplied load.
- **Frequency:** the frequency or number of affected items, such as number of disconnected customers or lines.
- **Duration:** the duration of impact, such as outage duration and SAIDI (System Average Interruption Duration Index)[37]
- **Curve:** computed based on the performance curve or resilience curve, such as the area under the real performance curve and the area of the resilience trapezoid (see Figure 7)
- **Probability:** probability of different aspects, such as probability of system failure and LOLP (Loss of Load Probability)
- **Economic**: costs and economic impacts on society, such as cost of unsupplied load or loss of GRP (Gross Regional Product)
- **Social**: social effect of a disaster, such as number of people without electricity
- **Geographic**: geographic distribution of the impact, such as area affected
- **Safety and health**: effect on human life and health, such as loss of human life and unavailability of hospital beds

Research activities are ongoing to develop proper metrics for resilience to help e.g. regulators and utilities decide on resilience investment, though it's still challenging[38]. The concept of the **resilience trapezoid**, mentioned under the curve type, can be used to assess the critical resilience dimensions, including progress of degradation, duration, and restorative phases.

[34] E. Vugrin, A. Castillo, and C. Silva-Monroy, ``Resilience metrics for the electric power system: A performance-based approach,'' Sandia Nat. Laboratories, Albuquerque, NM, USA, Tech. Rep. SAND2017-1493, 2017.
[35] J.-P. Wattson, et.al., "Conceptual Framework for Developing Resilience Metrics for the Electricity, Oil, and Gas Sectors in the United States", Sandia Nat. Laboratories, Albuquerque, NM, USA, Tech. Rep. SAND2014-18019, 2015.
[36] R. Habibollah, V. Vahid, M. Kamyar , Power Systems Resilience Metrics: A Comprehensive Review of Challenges and Outlook, MDPI, 20 November 2020.
[37] Defined in the IEEE Guide for Electric Power Distribution Reliability Indices
[38] https://www.nrel.gov/docs/fy20osti/74241.pdf

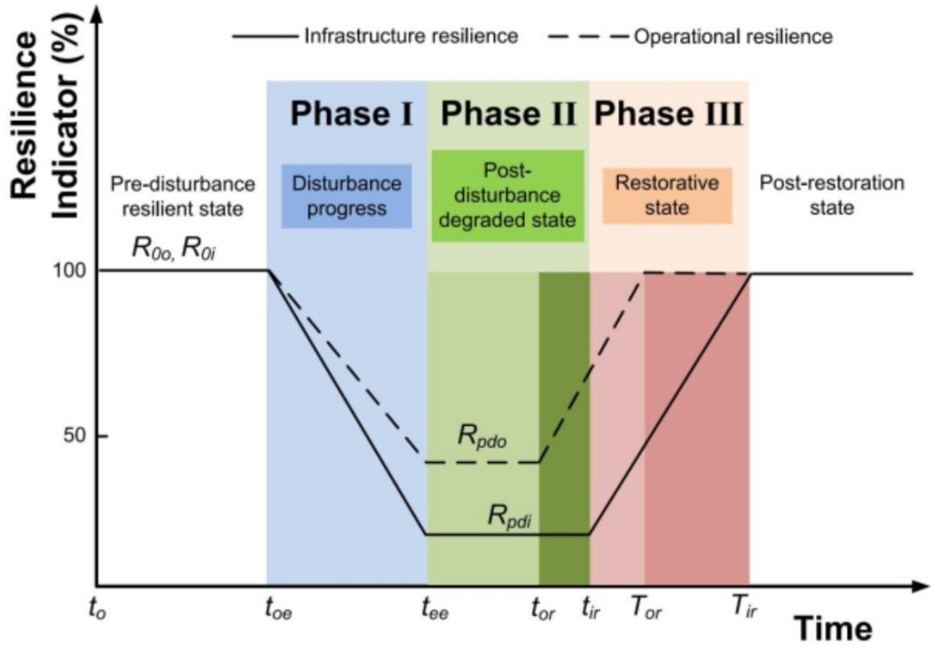


Figure 7: Resilience Trapezoid, from [39]

A quantification utilizing the resilience trapezoid could look like illustrated in Figure 7, which depicts the states which a power system might reside in during an event as well as the transition between these states.

3.3 Requirements to integrate flexibility sources and services

The energy sector is facing a major challenge to meet the growing electricity demand, which will require massive infrastructure investments. However, the inability to accurately determine the direction in which technological development will go has a significant impact on the investment decision-making process.

The shape of the new energy market will largely depend on the type of new technologies which will be used, their distribution in the area of network operators and their universal availability. The network requirements for integration of flexibility sources as well as the possibilities related to management of flexibility services are closely related to the development of smart grids. Figure 8.

To integrate and manage flexibility sources, new monitoring, control and data collection functions will be needed, as well as increasing the scope and use of existing ones. The existing network infrastructure, such as power lines and stations, need to be equipped with measurement systems, automation devices, as well as communication devices. Such an integrated structure should be managed by dedicated IT systems enabling the implementation of monitoring, control and automation processes.

[39] Y. Tan, "Power System Resilience under Natural Disasters", Doctoral thesis, University of Washington, 2018

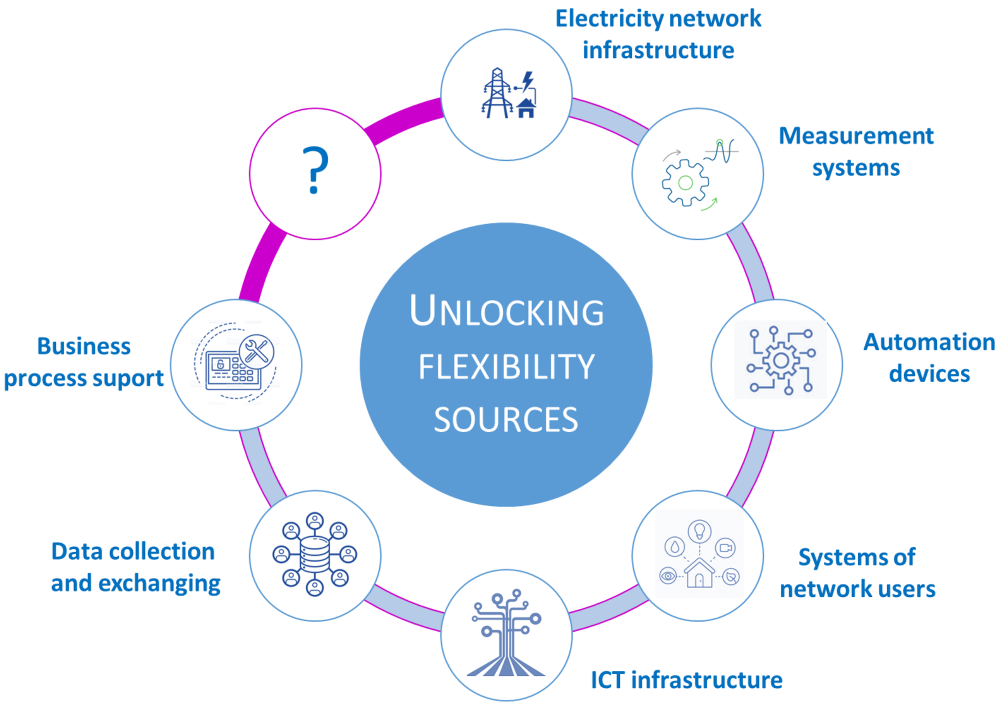


Figure 8: The main components to integrate flexibility sources

The requirements for the future grid to integrate flexibility sources include the elements of transmission & distribution, and the ICT infrastructure, with the main components:

Electricity network infrastructure: The modernization and expansion of this infrastructure will need to consider the requirements related to the introduction of smart grids. Therefore, it will not be a simple duplication of the existing patterns, but the introduction of advanced technical solutions. They will enable, among other things, remote supervision of devices, self-diagnosis, monitoring, adaptation to work in difficult climatic conditions.

Measurement systems and automation devices: These elements are used to measure the state of the network and to perform autonomous functions of automation related to ensuring the continuity and reliability of electricity supplies to consumers. The most important part are automatic electric power protection automatics systems. They include sensors and converters of electrical and non-electrical quantities, auxiliary relays, and control devices.

Measurement systems of network users: These elements are used to measure the quantities that characterize the energy flow at supply points and network characteristic points. They include measurements of municipal and industrial recipients, producers, prosumers, other operators, transformer stations, selected lines and circuits. The scope of the measurement includes basic electrical quantities as well as collecting information about the quality and reliability of supplies at the measurement site.

ICT infrastructure and platforms for collecting and exchanging data: The telecommunications infrastructure will be a key element of the network's equipment. It will ensure the possibility of transferring large amount of data, both from the customers and devices to decision-making centres, and in the opposite direction. In this way, it will provide information to manage and control the network and perform functions that require interaction with the end user, e.g. demand management, load control, reporting and implementation of flexibility services. The development of the telecommunications infrastructure will be one of the most important undertakings in the process of integrating the sources of flexibility in the network, and the functions performed by it will become the basis for the operation of the new network. Acquiring data and making them available to other systems and entities is the basic requirement of integration.

Network management systems and business process support: Network management and business process support systems are now used as separate, loosely coupled systems. The introduction of new requirements for the network infrastructure will be related to the integration of applications within a coherent IT environment, the creation of applications dedicated to new needs related to the analysis of the network condition and support for business processes. The whole will be ensured by appropriate IT security.

3.4 Next level of Flexibility

All power systems have a certain degree of flexibility to continuously adapt generation to the actual demand. Volatility and uncertainty are not new to power systems as the load varies significantly over time and energy sources can fail unexpectedly. Conversely, vRES can temporarily make it difficult to achieve the system balance. Both wind and solar energy sources vary considerably over hours and days, sometimes in a predictable manner, but often the forecasting of their generation capacity is imperfect.

Symptoms of insufficient flexibility in the power system can include:

- difficulties in balancing supply and demand, causing frequency changes or the need to reduce load through load shedding;
- significant reductions in the supply of energy from renewable sources (curtailment), due to excessive supply together with transfer constraints;
- deviations from the scheduled power balance of an area, indicating the non-fulfilment of the balancing responsibility;
- negative energy prices, due to insufficient ability to reduce production and increase demand, together with transfer constraints;
- price volatility, due to transfer constraints together with limited availability of peak production units and demand reduction.

It is important to identify proper flexibility resources in terms of ensuring the secure operation of the power system. The technical part of flexibility relates to the physical capacity of assets in the power system, regarding the abilities of [40]:

- supply to follow change in load,
- demand to follow change in supply,
- energy storage to balance supply and demand, and
- grid infrastructure to allow supply to reach demand and storage.

Utilising robust indicators to evaluate available flexibilities may support operators to make informed decisions regarding the operational activities of managing the system. The operational part of flexibility relates to the operation of assets in the power system, constrained by [40]: technical capabilities of the assets, and regulatory and market environment.

The next level of flexibility:
Fully deployed and utilized for operation and planning of the power system, being integrated in procedures for long-term planning as well as in tools for stability support

Development of solutions providing the next level of flexibility is a hot topic in the power system sector. However, integrating flexibility solutions in the long-term planning, as well as integrating dependencies of flexibility solutions to provide stability supporting actions, involves significant risks, volatility, and uncertainty.

Reliable assessment of the available flexibility will provide information for determining investment priorities for increasing generation and transmission capacity. Taking the technical and operational parts of flexibility into account, the capability for change in the production / consumption balance which the system can achieve for a specific time horizon at a given operational scenario can be used as a measure of the available flexibility. This available flexibility may be limited by the speed with which the assets can respond, as well as by the amount of power/energy to be kept operational. Other inhibitor factors for flexibility may originate from the market and regulatory frameworks.

The integrated dependency of flexibility measures, as well as appropriate assessment of the availability of flexibility, directly impact the resiliency of the power system, therefore flexibility solutions intended to provide resilience support must be reliable and secure to provide the trust required for operation and planning. The recent extreme weather events draw attention to distributed energy resources, i.e., new sources of flexibility as a cost-effective measure to improve resilience. As the frequency and magnitude of extreme weather events become more difficult to predict due to climate change, large generators and grids become easier to fail and harder to restore. On the other hand, DERs such as building insulation, solar plus batteries and microgrids can help consumers withstand power outages[41].

[40] IRENA, "*Power system flexibility for the energy transition. Part I: Overview for policy makers*", ISBN: 978-92-9260-089-1, 2018,
[41] https://www.canarymedia.com/articles/climate-crisis/hurricane-driven-blackouts-in-new-orleans-send-a-dire-warning-about-the-need-for-distributed-energy

4. FLEXIBILITY AND SOCIETAL TRANSFORMATION

The local dimension has emerged in the electrical system and is as relevant as the central dimension due to the new framework of the power sector where consumers are placed at the central part. The new generation of consumers will become active and will be ready to provide system services. Therefore, this section will show its usefulness in using local assets in system balancing as well as in TSO- DSO congestion management, especially now when DSOs will be posed with many local grid constraints. These issues should be solved through cooperation between all system actors and the market parties including aggregators, local energy communities, and single end users, that can solve the grid constraints.

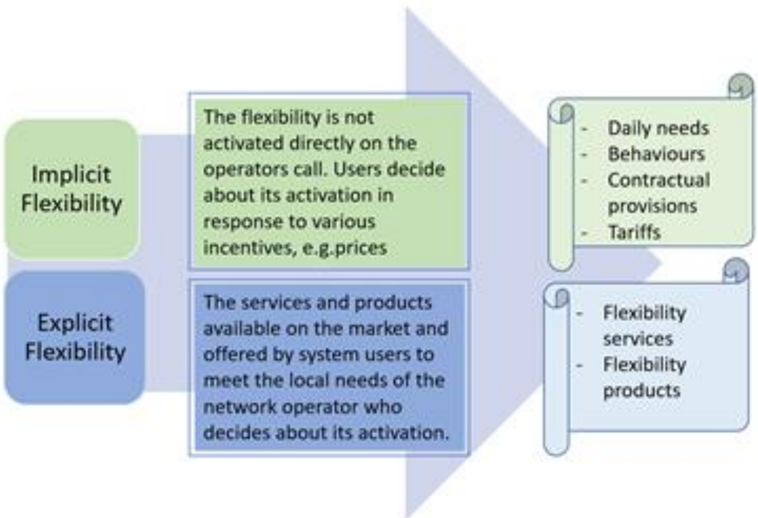
4.1 Explicit and implicit demand flexibility

Demand side flexibility or flexibility from demand side response can be defined as[42] the ability of a grid user to deviate from its normal electricity consumption or production profile, in response to price signals or market incentives [43].
In this sense, demand side flexibility refers to enabling final customers to become active in the market but also to system operators to make best use of this flexibility to ensure efficient system operation. For this reason, it is essential to understand the two possibilities that already exist for active demand-side participation in the energy market: explicit and implicit.
Explicit and implicit demand flexibility can be defined as [42]:

- **Implicit demand-side flexibility** is the consumer's reaction to price signals. Where consumers have the possibility to choose hourly or shorter-term market pricing, reflecting variability on the market and the network, they can adapt their behaviour (through automation or personal choices) to save on energy expenses. This type of Demand-Side Flexibility is often referred to as "price-based" demand-side flexibility.
- **Explicit demand-side flexibility** is committed, dispatchable flexibility that can be traded (similar to generation flexibility) on the different energy markets (wholesale, balancing, system support and reserves markets). This is usually facilitated and managed by an aggregator that can be an independent service provider or a supplier. This form of Demand-Side Flexibility is often referred to as "incentive driven" demand-side flexibility.

Both types of demand flexibility are complementary and can coexist allowing grid users to participate and exploit the full spectrum of system benefits from the use of flexible mechanisms in an efficient energy system. But the success of these mechanisms is strongly dependent on the user acceptance and engagement. In general, there is a general lack of customer awareness about what opportunities there are to engage in demand side flexibility.

Referring to the division of flexibility presented in Figure 2, the level of behaviour of power system users is related to flexibility from the users' point of view, Figure 9. These behaviours overlap but have different incentives. For example, for the power system, a behaviour of the system user consisting of the daily evening charging of an electric car is understood in terms of the need to ensure adequate flexibility in the system for the needs of the charging, while for system users satisfying their daily needs, the behaviour will not matter until when asked/incentivised to provide flexibility.



[42] European Smart Grids Task Force Expert Group 3, "*Final Report: Demand Side Flexibility Perceived barriers and proposed recommendations*", 2019
[43] This definition is in line with the terminology used in Directive (EU) 2019/944 where **demand response** is defined as "*the change of electricity load by final customers from their normal or current consumption patterns in response to market signals, including in response to time-variable electricity prices or incentive payments, or in response to the acceptance of the final customer's bid to sell demand reduction or increase at a price in an organised market as defined in point (4) of Article 2 of Commission Implementing Regulation (EU) No 1348/2014, whether alone or through aggregation*", Article 2, Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU.

Figure 9: General classification of flexibility resulting from the behaviour of system users[44].

From this perspective, the level of user behaviour is understood as the ability of system users to offer activities aimed at reducing or increasing the load or generation in the form of power change, or offering other services required at a given moment to guarantee stable operation of the network. This type of flexibility is also called explicit flexibility, that is, one that must be activated for it to occur. This happens at the request / call of the grid operator[45].

The level of users' behaviour is also their behaviour resulting from everyday needs and habits. In other words, it is a latent flexibility, that is, one that exists in the system but is not activated directly on the grid operator's call. Its implementation occurs as a result of the network users having, for example, additional provisions in connection agreements concluded in order to provide certain behaviours. These are also tariff solutions that make the customer change their habits to achieve the benefits of the tariff they have, i.e., shifting their consumption by hours at lower prices guaranteed by the tariff. But also in the future, these may be tariffs with dynamic prices, which, depending on their target structure, will constitute a certain source of flexibility that can be obtained. Nevertheless, flexibility level caused by customer behaviour not related to the grid operator's explicit call, sometimes may lead to unfavourable phenomena on the network, which may cause grid constrains Then, if the available technical capabilities are not sufficient to deal with these disturbances, it will be necessary to activate flexibility from system users. At this point, it is also worth noting that sudden problems with the operation of the network in a certain area may mean that the grid operator will need to activate non-market-based redispatching mechanisms if there are no market flexibility available in the affected area.

Solutions based on implicit demand-side flexibility are based on time dependent local tariffs, like time-of-use, dynamic or real-time-pricing, and can be technically implemented in a relatively simple way but they can be complex from the end-users' point of view. In this regard, the European Union Agency for the Cooperation of Energy Regulators (ACER) stated in its "Report on Distribution Tariff Methodologies in Europe"[46] that advanced differentiation in time and location through dynamic tariffs could further increase tariffs' cost reflectivity and incentivise efficient network behaviour, but such differentiation is rather complex, requires a sufficient level of automation, and may therefore contradict other principles.

Explicit demand-side flexibility can be offered by grid users that have significant flexible resources and usually without heavy impact on consumer's behaviour. These products could be marketed as well by an aggregator. The way these flexible products can be used by system operators is already described in the existing network codes or will need to be developed in the future ones.

Otherwise, distribution and transmission system operators are responsible for ensuring that the electricity in the system can flow between their grid users. From their perspective, demand side flexibility can be used to guarantee that sufficient network capacity is always available, complementary to the reinforcement or construction of new electricity infrastructure. Technically, it is possible to solve the problem of grid capacity through the flexibility provided by demand-response participants and be used by system operators to reduce loads on their networks and have an alternative to grid capacity investments in certain cases.

4.2 When demand side flexibility is already in place

In the previous section, the difference between explicit and implicit flexibility and it possible applications have been described.
In the case of explicit flexibility, its use in real systems, for example by means of demand side response programs for customers and aggregators who have the ability to reduce their demand, try to fulfil three main criteria. In the first place, it is essential to have a better exploitation of the potential offered by these flexible resources, achieving an optimal utilization. The use of the different types of alternative resources, such as demand side response and storage (e.g. from electric vehicles), and their participation in the wholesale market should happen on equal terms with the utilization of conventional units. Nevertheless, these programs are currently offered or procured only by TSOs and there is still no such possibility for DSOs to do it independently and the use of flexible resources is still incipient particularly for TSOs.

Secondly, the secure operation of the system is an overarching principle, and it must be combined with the search of efficiency, for instance, avoiding that the activation of flexible resources in a certain point of the network for balancing purposes creates local congestion and vice-versa. For this reason, and as mentioned in the previous paragraph, explicit flexibility from distributed resources needs to be considered to help in grid management both at the distribution and transmission level. System operators have always had as a top priority the secure and efficient operation of power systems and in the context of flexibility procurement, this also means that TSOs and DSOs will have to cooperate for the planning and the operation of their grids. TSOs and DSOs currently cooperate and exchange information, however this exchange will have to be reinforced to also guarantee the efficient use of resources and secure operation of flexibility at DSO level.

And the third criterion is the user perspective. There is a real need to facilitate market development, meaning that the integration of flexible resources into energy and service markets is an objective per se. The harmonization of the electricity markets in Europe, have already achieved important milestones such as the implementation of market coupling for the day-ahead market and the continuous intraday market, but is mainly focused on the transmission system. To incorporate flexibility mechanisms at DSO level, new services and products have to be clearly defined in a technology-neutral manner to enable the participation of different kinds of flexible resources. Another problem is that DSOs may lack economic incentives to use these resources.

[44] E. Mataczyńska, *Usługi elastyczności. Możliwości interpretacyjne zapisów pakietu Czysta Energia dla wszystkich Europejczyków*, Report IPE, 2020
[45] European Smart Grids Task Force Expert Group 3, "*Demand Side Flexibility Perceived barriers and proposed recommendations*", 2019
[46] European Union Agency for the Cooperation of Energy Regulators, "*Report on Distribution Tariff Methodologies in Europe*", 2021

From the above, some barriers to the full deployment of flexibility use by system operators can be identified:

- **Optimal Utilization of Resources**. The use of flexibility is already mainly by TSOs, although still limited to certain types and sizes. On the other hand, DSOs still do not use distributed flexibility in the daily operations.
- **Secure and Efficient Operation**. New regulation (e.g., a new Network Code on Demand Side Flexibility) and procedures are required to enable DSOs to use flexibility and also a proper coordination with TSOs.
- **Facilitate Market Development**. Implementation of the existing Network Codes is an ongoing process and may bring harmonization of products and services at TSO level, but distributed flexibility still needs a new Network Code to include mechanisms and product characteristics for the provision of DER flexibility at DSO level.

Regarding implicit flexibility, network tariffs scheme, in which customers can choose the most appropriate ones depending on their needs, are the main tool to provide incentives for efficient usage of the grid to network users. The conditions proposed in such dynamic tariffs contribute to shaping consumer behaviour because network users are exposed to price signals that reflect those changes in their utilization of the grid affect future network costs and thus providing additional value to the electricity network. In this sense, the tariff design should be targeted at reducing both the system peak and individual peaks.

At the current stage, technology is not sufficiently mature in all countries to allow the efficient use of dynamic tariffs on smaller users as it requires a sufficient smart meter roll-out and a high level of automation. As an example, in 9 Member States, time-differentiation is only energy-based and in 8 Member States time differentiation is both power and energy-based. Since dynamic tariffs are not implemented in any Member State, this option will become more viable in the coming years as grid digitalization progresses and smarter networks are in common use in the different countries.

As a recommendation, the implementation of implicit flexibility by means of network tariff schemes must be preceded by a thorough cost-benefit analysis in each country. Considering the fact that dynamic tariffs come with administrative costs and complexity, principles such as simplicity and predictability are especially important to design the correct schemes.

4.3 Load shedding and flexibility options

The concept is how load shedding can evolve and merge with demand side response (DSR): today we have, at one end, some load modulation through DSR and at the other end, interruptible loads, which are a very rough way of user's-based load shedding (on/off and quite randomly applied). In between, many custom-tailored load flexibility options can be designed before arriving to abrupt, undesired, and rather indiscriminate load shedding (typically by electric area = secondary substation). We can name this path as "smart load shedding".

For example, an automatic or semi-automatic arrangement that shutdown specific part of the load, for example non necessary at least on short term like heating or EV charging in case of low frequency or low voltage situations, would be part of the resilience measures made possible by tools and processes developed primarily for flexibility provision. A similar system is in place in the state of Queensland, Australia; the distribution network owner uses a 1,050Hz signal to disconnect several hundred MW of hot water systems to flatten the load profile during peak demand or other instances as needed. This is, however, manual rather than automated.

5. FLEXIBILITY FEATURES BENEFICIAL FOR RESILIENCE

The power systems are prone to be affected by risk and uncertainty associated with known and unknown challenges. The design of resilient and flexible power system requires the understanding of risks and uncertainties. In this chapter various examples and initiatives are presented, regarding e.g. alternative grid development, flexibility for operation and planning.

5.1 Risk management, network development and energy transition

Uncertainty can be categorized as randomness or "known unknowns" and lack of knowledge or "unknown unknowns".[47] Randomness is an independent feature associated with the nature of the uncertainty whereas lack of knowledge can be improved by knowledge sharing, data transfer, and detailed analysis. The uncertainty in input data can propagate into the design and investment decisions and affect the outcomes. The risk and uncertainty become important due to the need to maintain system resiliency against events while ensuring reliability. The occurrences of extraordinary events in power systems are difficult to be predicted accurately, but the probabilities of occurrences may be estimated with a fair degree of certainty.

A system becomes resilient from proper **risk-management** practices. The risk management practices are required to be a structured and comprehensive with cause-consequence analysis. Prevention and control strategies in the cause-consequence analysis are designed to limit the intensity, extent and subsequent consequences of extraordinary events. The risk management strategy is broadly classified into Stress avoidance, Stress resistance and Strain adjustment.[48] The strain adjustment is basically a mitigation strategy and deals with flexibility of the system to adapt to stress. Flexible design helps in achieving the objectives as it factors uncertainty and variability in power flow.

Power systems are in general designed based on the N-1 criterion, to achieve high degree of reliability with economy. The flexible operation in generation, transmission and distribution provides a degree of reliability owing to their capability to adapt to new scenarios. The flexibility in generation is supporting by providing fast ramping and wide ranges of operation. The transmission is becoming more flexible owing to the augmentation in HVDC and FACTS devices, allowing for enhanced control of the power flow. The distribution side flexibility may utilize Distribution Management Systems to its advantages. The capability of shifting of loads from one feeder to other is a resilience based flexible approach. Demand Response also adds to flexibility and resiliency. The flexible design could help in adopting to emergency conditions, where these features act as a reserve in the hands of the system operator and in case of emergency scenarios can be easily put in operation.

To prevent damage from an extraordinary event, an accurate understanding of the possible threats from that event is required. This is obtained through the use of tools to analyse and update the design basis threats such as earthquakes, tsunamis, and hurricanes. Similarly, advances in the reliability of emergency generating units and efficient power usage during a prolonged loss of supply are also important to prevent damage from events.[49] Transmission system element failure are less frequent than distribution equipment, but their failure affects larger areas, and outage durations may be much longer. This fact, combined with the high cost per transmission equipment require greater attention. In comparison to generation, transmission assets are extended to large geographical areas and are more prone to failures. The transmission line spans are also more exposed when it comes to thunderstorms/cyclones etc. The following practices are important to enhance the resiliency of transmission systems:

i. Underground cables: Overhead transmission lines are prone to vegetation faults, cyclones, lightning strikes etc. Underground cables at selective locations may improve resiliency. It should however be noted that underground cable faults may have significant duration.
ii. Periodic line maintenance: Standard practices of line maintenance help in avoiding unnecessary outage due to low clearances on account of vegetation or any other reason.
iii. Spare availability: Can reduce the downtimes significantly.
iv. Database of personnel and material: An updated database of available resources in the form of manpower and Emergency Restoration Service help in timely mobilization during crisis situations.

From the **energy transition** point of view infrastructure investments can increase resilience including redundancy and supporting solution automation and network development as valuable solutions to ensure security and quality of supply of the systems.

As the energy transition scales up and new challenges to integrate intermittent renewable power generation arise, the use of more adaptable solutions will become critical to ensure grid stability. On the other hand, natural disasters and extreme weather events are expected to increase following the climate change, leading to higher risks for distribution and transmission networks.

In parallel with conventional solutions, alternative grid development solutions, also called non-wire alternatives, emerge which use non-traditional solutions such as advanced monitoring and control of distributed energy resources and demand to defer or replace the need for specific infrastructure upgrades. In this regard, Art. 32 of the Directive (EU) 2019/944 "Incentives for the use of flexibility in distribution networks"[50] states that "the development of a distribution system shall be based on a transparent network **development plan that the**

[47] T.Hardy, M. Knight, A. Veeramany, & J. Woodward, "*Resilience Metric Formulation Considering Transactive Systems*", Pacific Northwest National Laboratory, 2018
[48] S Widergren; A Shankar; B Kelley; J Taft; R Melton; "*Toward a Practical Theory of Grid Resilience A Grid Architectural Approach*", April 2018, Northwest National Laboratory.
[49] Electric Power Research Institute, "*Electric Power System Flexibility: Challenges & Opportunities*", 2016
[50] European Parliament and the Council of the European Union, Article 32 (3), Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June

distribution system operator shall publish at least every two years and shall submit to the regulatory authority. The network development plan shall provide transparency on the medium and long-term flexibility services needed and shall set out the planned investments for the next five-to-ten years, with particular emphasis on the main distribution infrastructure which is required in order to connect new generation capacity and new loads, including recharging points for electric vehicles. **The network development plan shall also include the use of demand response, energy efficiency, energy storage facilities or other resources that the distribution system operator is to use as an alternative to system expansion**."

With the publication of this Directive, flexible assets connected to networks become available for TSOs and DSOs to manage congestions on their networks. In the case of DSOs, for the first time, they have a framework to use flexibility and optimise network investment decisions. Flexibility will be a valid option as long as reliable and suitable flexibility resources can be developed and the service is more cost efficient than traditional grid reinforcement.

At this point, a relevant question is how to appropriately value flexibility services in order to determine whether it is the best value solution to a particular network issue relative to existing solutions. A comparative approach could be used; for example, for any particular investment scenario, the amount that the system operator is willing to pay for flexibility is determined by the cost and value of the counterfactual solution avoided. The annual service expense could be calculated by converting the regulatory cost of counterfactual into an annual amount and, consequently, equating the value of the flexibility solution with that of the counterfactual, depending on the duration of the flexibility services contract.

In consequence, an internal assessment could be seen as a tool to decide if the use of flexibility in certain cases could be an alternative to grid infrastructure investments. Following this assessment, a flexibility solution may not be appropriate in all cases, for instance, with regard to the criticality or timeliness of the connection. In this sense, infrastructure investments can sometimes be the only solution, and can be seen as a key enabler to foster demand participation and the development of new flexibility services.

Furthermore, the economic and regulatory angles are inseparable from the decision process and, for this reason, National Regulatory Authorities should acknowledge that more tailored remuneration schemes are required to make viable flexible-based solutions in addition to traditional grid reinforcements to the efficient provision of network services. In short, costs and economic incentives for market-based flexible solutions should be acknowledged by the regulatory framework.

5.2 Reliable flexibility for operators

In terms of power system management, flexibility have been developed for grid operation with high variable RES penetration. System operators are primarily focused on security and reliability standards based on meeting peak demand, but this approach does not fully follow the variable and uncertain nature of the network utilisation especially due to the increased penetration of distributed energy resources and the growing electrification of the economy.

The mechanisms for European TSOs to achieve balance in transmission grids are already implemented through the existing networks codes and their subsequent implementation in the different Member States. Additionally, the Directive (EU) 2019/944 also states that "Member States shall provide the necessary regulatory framework to allow and provide incentives to distribution system operators to procure flexibility services, including congestion management in their areas". These services can materialize in the form of solutions for congestion management, as well as non-frequency ancillary services such as steady state voltage control, fast reactive current injections, inertia for local grid stability, short-circuit current, black start capability and island operation capability. The ability of system operators to use more fine-tuned and creative flexibility products will be enhanced with increasing visibility and control of the network through digitalisation and adaptation to new technologies. This follows the solutions and requirements on resilience, with novel solutions required as the conventional ones become diminished in the same time as the system gets exposed to increased stress, Figure 10.

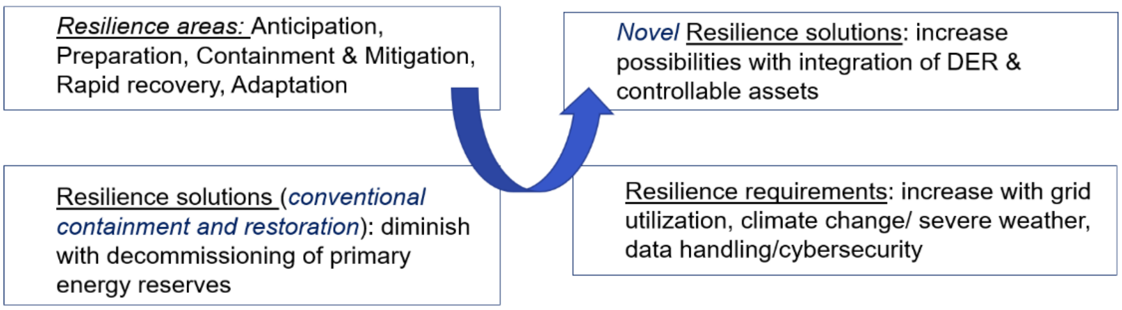


Figure 10: Resilience solution and requirements.

The needs of using flexibility by operators could be divided as follows[51]:

2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU

[51] European Smart Grids Task Force Expert Group 3, *"Regulatory Recommendations for the Deployment of Flexibility"*, 2015,

For TSO:
1) Frequency regulation (FCR, FRR, RR)[52],
2) Reactive power regulation,
3) System balancing,
4) Congestion management

On the other hand, DSOs do not have such possibilities due to the lack of unambiguous regulations that would allow the development of a flexibility services market.

For DSO
1) Short-term local congestion management,
2) Voltage control / reactive power management
3) Long term capacity grid management.

The development of such market and the change of the DSO's role from technical support to a neutral market facilitator on the way to activation of consumers should be another important step on the way to the implementation of the Clean Energy for all Europeans package[53].

Rapid customers activation and the subsequent change of the network management model in the bottom-up direction seems to be the first upcoming step. Due to the rapid development of distributed DER, stabilizing the grid at the local level supports the stable operation of the entire power system. Local areas of balancing and congestion management at the distribution network level, with the use of small sources connected to the distribution networks, will thus become the basis of the new energy market model. Local balancing areas can prove valuable in the event of network performance problems caused by extraordinary events. The problems of the entire network should be viewed through the prism of its weakest points and strengthened locally in such a way as to make them more resilient to various disturbances in the future.

Flexibility from **demand side can offer solutions for** both the planning and **operation** of electricity networks considering that most of the existing planning schemes do not include the flexibility requirements of the power system that consider the customers' flexibility characteristics such as start-up times or ramp up/down ratios. Hence, to use those flexibility services, system operators need to assess dynamic network conditions to establish how much flexibility capacity is required, when it is needed and where on the network flexibility providers can be more efficient. At the same time, some levels of analysis and modelling of systems are required, including real-time state estimation based on real-time data and sophisticated demand forecasts tools using metering data and bottom-up aggregation of various load categories.

The previous arguments are more relevant considering that the frequency and intensity of disastrous events are expected to increase due to climate change and cyber-attacks, just to mention two real threats. Network resilience is often linked to the capacities of electrical infrastructures to mitigate and absorb shocks and rapid recovery to pre-disaster conditions. Improving critical infrastructure resilience is particularly important in a context of increasing electrification and high penetration of renewables and for this reason alternative, flexible solutions, as the ones described in this chapter, can be a real solution for system operators to retain the basic structural functionality of the power systems.

Many of the ongoing projects and practices, some of which are presented in the Appendix, supported by innovative demo and piloting solutions can provide highly relevant knowledge to the question of *How can flexibility support resilience?*

Some of the mentioned solutions include projects focus on:
- novel solutions for system protection schemes and operation (e.g. islanding, congestion mitigation) enabled through fast control of load and distributed generation,
- situational awareness and system state observability, enabled by increased monitoring, communication, and data exchange
- cyber security, highlighted by the utilisation of common platforms for data sharing and AI & machine learning solutions, being part of the digitalisation of the power system

Furthermore, standardization of solutions (architecture, tools, platforms) is important to increase the reliability and acceptance for large scale deployment of flexibility solutions.

5.3 Resilience, system flexibility and grid planning

The design and building of new generators and transmission system takes long time and the investment planning process is the initial step to ensure that the power system will have sufficient flexibility and resilience. In regulated scenarios, this function was carried out via a centralized planning model in which industry participants and government agencies jointly assess potential requirements for resiliency. In market-based scenario, sufficient investment signals regarding the potential need for flexibility are required. In the absence of sufficient investment clarity, the power system may lack the ability to operate with sufficient resilience. The resilience is thus factored at the long-term planning stage in several power systems. For instance, the need of black start sources are required to be planned, so that they integrate with the rest of the system. Grid planning may also consider the geography and locational aspects. For example, in case the grid is passing through an area prone to flooding, the planning shall factor the outage of network/station in flooding season and be designed accordingly.

[52] Frequency Containment Reserves, Frequency Restoration Reserves, Replacement Reserves
[53] European Commission, "*Clean energy for all Europeans package*" 2021, https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en

Flexibility is relevant to many aspects of the planning process. [54] Traditional processes focused on ensuring sufficient generation and transmission capacity to reliably meet demand during peak conditions. In processes considering broader view of resilience, can ensure that systems can also meet and deliver the flexibility required for successful operation under all scenarios.

Investment planning, in the form of network development plans, should be the result of a procedure that gives an overview of a complete grid development, with particular emphasis on the main transmission and distribution infrastructure which is required in order to connect new generation capacity and new loads. Usually, it is necessary to use reference scenarios to identify the technical characteristics of main investments, especially investments which have the technical and economic potential to be deferred or replaced by flexibility. Nevertheless, for each network development case, system operators will have to analyse the feasibility and cost-effectiveness of any flexibility solution versus investments in traditional infrastructures. As a result, the network development plan will highlight areas or parts of the grid where there is a potential need for flexibility services.

In this sense, implementation of the flexible investment planning is a relevant aspect to consider by system operators as an alternative to their classic infrastructure development plans. When considering the potential of flexibility from a resilient perspective, it is important to develop mechanisms based on forecast changes in customer load and plan upgrades or grid extensions, and also to anticipate asset replacement needs as equipment reaches the end of its useful life.

Accordingly, some of the solutions which system operators take into consideration when addressing needs in development plans include:

- Optimising infrastructure investments.
- Deferring or avoiding asset reinforcements.
- Implementing more efficiently planned maintenance, asset replacements, and connection works.
- Considering unplanned interruptions by mitigating effect of network outages, and thus minimising impact on customers.
- Improving quality of supply.
- Reducing network implementation timescales.
- Optimising infrastructure use.
- Increasing capacity of existing grid assets to enable new renewable generation.

Regarding planning of lower voltage levels, it is challenging to develop long-term development plans since these to a higher extent depend on short economic cycles and social dynamics. Distribution system operators managing lower voltages need to improve and refine their forecasts for electricity use, to ensure that the capability of the distribution system is expanded in a cost-effective manner using smart solutions and intelligent asset development, and, at the same time, helping to proactively determine the development of the distribution system at higher voltage levels.

Investment planning activities are also significantly affected by RES variability, which becomes more complex and affected by a high level of uncertainty. Grid investments are capital intensive and infrastructures lifetime spans over several decades. Due to widespread RES and DER deployment, the generation and load scenarios upon which the cost-benefit analyses for new grid infrastructures are based are continuously and rapidly changing. As a consequence, when a new line is commissioned, the technical-economic benefits it was initially supposed to reap could prove significantly lower than expected. Additionally, building new lines meets more and more public opposition, which makes planning activities even longer and affected by uncertainties. Variable flows from RES are generating a new type of intermittent congestion which can sometimes be better compensated by resorting to system flexibility: in many cases, an investment in a new line/cable would not be economically justified. Thus, establishing new T&D grid planning methodologies, considering e.g. the opportunity to install storage devices and other flexible alternatives to building new lines, is an important step forward. With local solutions to cope with RES generation peaks, the congestion in the grid can be reduced in less expensive and less environment-impacting manners. At the same time, the increase of flexibility available in the network will positively contribute to its resilience. (See details in Appendix A.)

5.4 Grid services and Markets

Inclusion of flexibility should be associated with the occurrence of signals that the balance stability of the system is at risk. In this case, activation of the flexibility sources may occur because of receiving frequency signals with a dangerous degree of system imbalance. This type of flexibility is secured by the presence of balancing offers in the market, and therefore its activation uses balancing services offered by the market. These can be services related to both energy and power.

The balance flexibility in its entirety refers to the needs related to the current system balancing, that is, maintaining stable and safe network operation, especially in the frequency range. This means that the source of activation of this flexibility should be signals related to frequency and the observed dynamics of their changes. Such activities are appropriate for the transmission system operator which ensures the balancing of the power system at the national level. Pursuant to the regulations in force included in the Balancing Network Code (EB GL), these obligations are specific to the transmission system operator only and are performed through balancing services. The result of the implementation of balancing services will be a decrease in generation and an increase in load, or vice versa - an increase in generation and a decrease in load.

[54] J. Cochran, et al, *"Flexibility in 21st Century Power Systems", National Renewable Energy Laboratory, 2014*

European perspective:
Day-ahead market. EUPHEMIA is the algorithm that has been developed to solve the problem associated with the coupling of the day-ahead power markets in the PCR region. First, Market participants start by submitting their orders to their respective power Exchange. All these orders are collected and submitted to Euphemia that must decide which orders are to be executed and which orders are to be rejected in accordance with the prices to be published such that:

- The social welfare (consumer surplus + producer surplus + congestion rent across the regions) generated by the executed orders is maximal.
- The power flows induced by the executed orders, resulting in the net positions do not exceed the capacity of the relevant network elements.

Euphemia handles standard and more sophisticated order types with all their requirements. It aims at rapidly finding a good first solution from which it continues trying to improve and increase the overall welfare. [55]

Intraday Market. The XBID Programme started as a joint initiative by Power Exchanges and TSOs from 11 countries, to create a coupled integrated intraday cross-border market. Meanwhile the XBID Platform has been confirmed as the Single Intraday Coupling (SIDC) which shall enable continuous cross-border trading across Europe. [56] This means that orders entered by market participants for continuous matching in one country can be matched by orders similarly submitted by market participants in any other country within the project's reach as long as transmission capacity is available. The intraday solution supports both explicit (where requested by NRAs) and implicit continuous trading and is in line with the EU Target model for an integrated intraday market. The purpose of the XBID initiative is to increase the overall efficiency of intraday trading.

However, the flexibility can be used in many different markets and products. For example, if every user (or buyer) of demand side flexibility organizes its own market, this could lead to market fragmentation and lack of transparency as well as to problems with the coordination between different market processes (e.g. double activation, etc.).

A survey of currently used platforms and their functions, flexibility, and target market, shows that functions mostly implemented using a not paid platform. Regarding the problem of using flexibility in many different market and products, many energy stakeholders consider that developing a limited/regulated number of fully integrated markets is the best way to overcome this problem. It is uncertain if the target market model should be implemented based on one of the existing frameworks on common integral market designs for the trading of flexible energy use.[57]

5.5 Flexibility coordination in Operation

In practice, power system flexibility features are very much dependent on real time operating conditions. They depend on the status of generation, the capabilities of load, and seasonal and diurnal characteristics of wind, solar, and hydro resources, among other factors.
Flexibility in operation is required to maintain the load-generation balance. The inability to implement flexibility features may cause excessively high or low frequency fluctuations. Inflexible operation may also cause wide variations in area control errors and reduced reliability. The flexibility in operation are therefore important features which need to be ensured. The operational flexibility can be increased via solutions such as providing improved weather forecasts or enhanced visualization and monitor of the extent of an extraordinary event and projection of forecasted events. For example, in the Indian power system, solutions are available which provide near to real time information about cyclones, thunderstorms, floods etc. (see further details in Appendix T.) The control available with operators, like ancillary services dispatch and HVDC power order variation, are enabling elements for taking timely actions in case of extreme scenarios. Using robust, engineering-based metrics for assessing flexibility as a component of a grid operation study can support system operators to make informed judgments about the tecno-economical optimal amount and mix of flexibility measures to implement during operation.

Considering the TSO and DSO coordination in terms of grid services from a flexibility viewpoint, both provided and utilized services can be as follows. The TSOs could be providing services to collect and share metering data, and may utilise services regarding frequency control and reserves, balancing, capacity reserves and management, and voltage control. DSOs could be providing services regarding metering data, load control, and voltage control, while utilising services regarding voltage control, congestion management, and backup power. New use cases where DSOs foresee the use of flexibility include: controlled islanding, operation under severe events, restoration control, and local grid balancing. Provided services to grid customers from both TSOs and DSOs can be flexible grid connection contracts. If case of connection costs applied to customers intending to connect into a weak grid, the cost of connection might become very expensive. In such case, a flexible grid connection contract might be an interesting option to reduce grid connection costs. The intention of the flexible connection contract is to avoid or postpone grid reinforcements while connecting new customer who is willing to be flexible. In practice, this may result in occasional production curtailment or demand management. [57]

[55] EUPHEMIA is a generic algorithm: there is no hard limit on the number of markets, orders or network constraints; all orders of the same type submitted by the participants are treated equally.
[56] XBID is based on a common IT system with one Shared Order Book (SOB), a Capacity Management Module (CMM) and a Shipping Module (SM).
[57] Interrface deliverable D2.2, "*Existing tools and services report*", 2019

Role	1st	2nd	3rd
Aggregator	Energy Storage Systems	Smart Metering	Demand Response
DSO	Smart Metering	Demand Response	LV online monitoring; Online Voltage Regulation; Smart Substation/Digital Transformers; IoT Grid Management Systems
TSO	Energy Storage Systems	Online Voltage Regulation	Smart Metering

Figure 11: Top 3 grid services considered most relevant for the future energy system by role, from [57]

Some of the main items for enabling utilisation of flexibility sources by grid operators are:

- Increased observability at all voltage levels - measurement data from demand, generation, and network state, are necessary for secure grid operation and to enable advanced grid control
- Systems to enabling safe and efficient identification and utilisation of available flexibility in the system in accordance with defined priorities
- Systems for identifying grid needs with possibility of assigning available flexibility sources and services
- Systems for analysing energy demand and advanced forecasting of production and load

The holistic LINK Solution provides an exciting alternative for operational flexibility across power grid and customer plants. It uses chains of secondary controls (links) as an instrument to realise the operational flexibility from both sides, generation and demand (see further details in Appendix S).

5.6 Sector coupling and System of Systems

Some of the biggest innovations and development opportunities in last decades concern battery and electrolyser technologies. Together with other advancements, such as increased electrification in other sectors, these technology areas make vital contributions in reduction of CO_2 emissions between 2030 and 2050 in our pathway. Innovation over the next ten years – not only through research and development (R&D) and demonstration but also through deployment – needs to be accompanied by the large-scale construction of the infrastructure. This will include pipelines to transport captured CO_2 as well as systems to move hydrogen between e.g. ports and industrial zones. Together with solutions to efficiently convert energy between carriers (e.g. Power-to-Gas), the sector integration will be strengthen with additional resilience built in the system as a whole. The increased interconnection of systems can be foreseen to become a "system of systems"[58], with the developed integrated solutions resulting in increased over-all efficiency, flexibility, and resilience.

It is also important to address the role of urban transformation in achieving climate goals. Specifically, to spur technological and process design innovations to develop climate-neutral urban neighbourhoods, like local energy communities, which could be building blocks of Positive Energy Districts (PED).

PEDs are energy-efficient, energy-flexible and net-zero urban areas which produce a local or regional surplus of renewable energy and actively manage this throughout the year to reach overall net-zero carbon status. PEDs require integration of different systems and infrastructure, including buildings, their users and regional energy, mobility and information and communication technology systems. Where the associated load can be assumed to feature significant flexibility, and its coordination, driven by more effective time-of-use rates and control technologies that enable building automation and smart EV charging strategies.

Thus, one of the important aspects is to transform existing urban structures toward climate-neutral neighbourhoods. For example, this could include addressing urban retrofitting strategies and managing complex ownership and stakeholder ecosystems and regulatory frameworks and ringing forward innovative solutions for public-private partnerships, business models, stakeholder mobilization and public involvement. A systemic view should be added here: after considering resilience of individual components and resilience of the combined set of components (interacting among them), a third step is to analyse if and how different portions of a sector-coupled energy system can reciprocally sustain in case of HILP events; for example, widespread electric vehicles batteries could serve as an extra local back-up source for privileged local loads. The ambition is to leverage on the complexity of future system, which definitely increase the risk of unexpected events, also as a resource to counteract them.

LINK solution enables the Sector Coupling[59] and Energy Communities as a PED building block[60]. Since the LINK solution was developed based on fractal principles, the same principles can be used in all structures (see further details in APPENDIX S). The optimisation of the electricity system and other energy systems is realised by coordinating and adapting the locally optimised systems.

[58] ETIP SNET, "Vision 2050", 2018, https://www.etip-snet.eu/etip-snet-vision-2050/
[59] ETIP SNET Position Paper, "*Smart Sector Integration, towards an EU System of Systems*", July 2020.
[60] INTERACT – Integration of Innovative Technologies of Positive Energy Districts into a Holistic Architecture, https://www.ped-interact.eu/

6. R&D AND INNOVATION NEEDS

In the last years, researchers and engineers are contributing a lot and assisting to a high-speed deployment of Renewable Energy Sources (RES) in electric Transmission and Distribution (T&D) grids as well as to an increased penetration of Distributed Energy Sources (DER) in distribution grids. Due to this effort, flexible resources and its variability gets closer to homes and society needs. The geographic dimensions of challenges range from local to regional and able to preserve system balancing notwithstanding the typical "variable" generation pattern of RES are more and more necessary.

Enhancing the resilience of digitalized energy systems

For smart grids, it is not sufficient to consider only the flexibility that the electricity-related parts of the power system can directly provide. The communication networks as well as other ICT parts have to be taken into account and to be made flexible and resilient. In the following, the areas of research necessary to achieve flexibility contributions for resilience are described, based on [61], [62], [63], [64].

Area 1: Resilience in and through distributed structures

In a power system dominated by renewables, the distributed energy resources (DERs) rather than large power plants must contribute to resilience. Generally, because of other and more complex incidents, new mechanisms like self-organization, self-healing, and self-defence have to come in place.

Therefore, research efforts should be directed in the following directions:

- general methods of self-organisation of DERs with special emphasis on artificial intelligence (machine learning, multi agent systems),
- self-organized defence against malicious attacks,
- optimization methods for maximum flexibility of pooled DERs,
- temporary islanding and distributed black start in case of blackouts and corresponding ICT requirements,
- plug and play solutions for renewable off-grid electricity,
- markets for conventional and new ancillary services,
- measurement of quality of service of ancillary services provided by DERs,
- control architectures,
- DSO-TSO interaction, coordination and data exchange emphasizing the role of the distribution grid and the respective DERs,
- potentials of cross-sector integration,
- involvement of customers and civic society, e.g. for acceptance, user involvement, device control, and user interaction), and
- opening up of consumption flexibilities of industrial manufacturing

Area 2: Cyber-resilience

In the future, the relevant ICT components and communication networks in and outside the energy sector are important to provide flexibility and contribute to a resilient energy system. New digitalization techniques will also play their part. Obviously, in a digitalized energy system, cyber-attacks pose an eminent threat.

Therefore, research efforts should be directed in the following directions:

- mutual dependencies of public and dedicated communication networks,
- resilient communication infrastructures,
- integration of the status of ICT components and networks into energy management systems and SCADA systems for an enhanced situational awareness and contingency management,
- Operation Technology (OT) systems, which are resilient against all kind of cyber incidents (e.g. with fallback solutions if parts of the OT are compromised, virtualization),
- cyber security by design (with emphasis on OT security, actors outside the typical, e.g. platforms of EV manufacturers),
- interoperability and standards to integrate DERs,
- digital twins (also distributed digital twins as part of multi agent systems),
- trust assessment of OT process data,
- distributed ledger technology, and
- resilience of software and service platforms

Area 3: System design and analysis

[61] ETIP SNET, "*ETIP SNET R&I Implementation Plan*", 2020
[62] ENTSO-E, "*ENTSO-E Research, Development & Innovation Roadmap 2020 – 2030*", 2020
[63] Department of energy, "*Quadrennial technology review*", 2015
[64] German National Academy of Sciences Leopoldina, acatech – National Academy of Science and Engineering, Union of the German Academies of Sciences and Humanities, "*The resilience of digitalised energy systems*", 2020

The future energy system is much more complex: The number of active components will be several orders of magnitude larger than today. The system behaviour will be more chaotic at times, so it will not follow well known statistical patterns. Tools are also needed to measure resilience in the face of novel, unexpected, or unknown disrupting incidents.

Therefore, research efforts should be directed in the following directions:

- holistic solutions encompassing relevant energy systems (e.g., appendix S, etc.)
- system-level control strategies,
- adaptive situation-dependent protection,
- holistic modelling and simulation (cyber-physical modelling, markets, customer behaviour, large scale/small scale, large/small time rates),
- test and validation approaches, adaptable metrics for resilience,
- system of systems architectures,
- constraints/requirements from market and regulation,
- managing system split under high renewables supply, and
- planning and design of distribution grids under the constraint of desired resilience by flexibility of DERs

Advancing network codes through the use of Regulatory sandboxes

The idea behind a sandbox finds its origin in software engineering: a sandbox – as in a testing environment – for running potentially unsafe codes, without the risk of infecting the entire system. A regulatory sandbox is not unique to the energy sector and has previously been introduced in other sectors such as banking and healthcare.

A good starting point of what the principle of a sandbox can be derived from its name: a safe playground in which to experiment, collect experiences and play without having to face the strict rules of the "real world". Whereas the sand of an actual sandbox protects against harm while playing, certain consumer safeguards are established to fulfil that task in its regulatory counterpart. Meanwhile clear entry and exit requirements, as well as a pre-defined scope, display the borders of the box.[65]'

The need for regulatory sandboxes is often related to solutions which were not thought of or were not necessary before, but which are related to new challenges for the energy system. Hence, the scope of experimenting mentioned and applied for most often are related to[66]:

- development of flexibility services for grid stability,
- reduction in environmental impacts,
- sector coupling,
- energy storage integration in the power sector, and
- management of local energy communities.

These main topics for experimenting with smart grids, in which sandboxes could be considered as possible instruments, require adaptations or clarification of rules and regulations, as the related use cases have not been part of the ordinary way of running the energy regime.

Accordingly, the main innovation goals which are considered as feasibly addressed with sandbox schemes are:

- new products (e.g., for energy management),
- new services (e.g., peer to peer exchange of energy and flexibility services),
- platform solutions (e.g., distributed ledgers with blockchains) ,
- new tariff-models (e.g., grid tariffs for battery storage) and
- new business models (e.g., local energy community).

Consequently, the purpose of the regulatory sandboxes is to reach mature, economically, and technically feasible solutions, and allow the next phase of deployment and implementation. The intention, therefore, is to take a more proactive approach to innovation, to identify whether current arrangements can always deliver the right outcomes; and explore where to adapt new approach to regulation so that today's innovators are better able to bring forward the products and services that tomorrow's energy system and consumers need. Over time, and as the system transitions, the rules that govern it will evolve very fast. But, where an innovator wants to trial something novel, or launch a new business now, some rules might be 'barriers' to making this happen.

In this context, there is a need to evolve the regulatory framework to respond and satisfy the new needs of system operators and grid users, achieving a balance and providing the safest possible environment for innovation and investment. Technological innovation may involve taking some risk, so, to promote it, it is important to have a safe environment where promoters and the regulator can work together to evaluate the benefits of new technologies and services before their final implementation. Regulatory sandboxes are an example of this approach and a valuable learning experience, whether to better understand the benefits of proposed solutions, the limitations imposed by

[65] Wolf-Georg RINGE, Christopher RUOF, "*Regulating Fintech in the EU: the Case for a Guided Sandbox*", European Journal of Risk Regulation, Volume 11 ,Issue 3 ,2020
[66] ISGAN Annex 2 Smart Grid Case Studies, "*Innovative Regulatory Approaches with Focus on Experimental Sandboxes*", Casebook, ISGAN, 2019

existing regulation, and to identify possible corrective measures that facilitate innovation.

Due to the complexity of the use of flexibility, Member States should start testing market-based flexibility procurement with pilot projects based on real use cases to effectively implement the flexible mechanisms as an alternative to grid reinforcement in certain cases. If they are not already included in the regulation, regulators should allow regulatory sandboxes outside the current regulation framework to test those pilot projects. It should be mentioned that this process may entail high technical and regulatory risks for system operators, and for this reason the costs incurred by these pilot activities for the system operators shall be acknowledged and fully recoverable, as such regulatory sandboxes usually guarantee.

The energy transition requires a fundamental re-think of energy regulation in Europe. Sandboxes should be part of reply to this: an agile, responsive, and adaptive way of working with all market parties to realise opportunities now, while in parallel redesigning markets and rewriting rulebooks to bring about major reform. This does not mean all new sandboxes' projects will be successful, nor does it mean that all activities will be universally beneficial to all consumers, to the system, to markets and to industry participants. The implications of different innovations for energy policy, regulation and practices will ultimately require trade-offs and decisions about the preferred features of tomorrow's energy system. The flexibility term, and especially flexibility services have to be tested very carefully to confirm the importance of such activities for the electricity system and for customers.

7. CONCLUSIONS & KEY MESSAGES

Both Flexibility and Resilience have been so far quite well addressed in the research community:

- Flexibility is being developed for grid operation with high vRES penetration, and starts being considered at the investment planning stage;
- Resilience is based on reliability, risk analysis, system interactions analysis; all these within the perimeter of the electric power system.

Power system resilience reflects the impact of severe events and is an overarching concept, that covers the whole spectrum of the power system from design and investment decisions to planning, operations, maintenance and asset management functions. As such, the concept of power system resilience applies to the planning time frame that looks to build resilience into the future network, as well as the operational time frame, in which security is managed by optimizing the inherent resilience of the existing power system.

Flexibility concerns the power systems ability to manage changes, with flexibility features able to improve the resilience characteristics of the broader view system of systems, provided that they are integrated in grid planning, in defence plans, and properly evaluated in the energy market design. Flexibility capabilities need to be considered from the planning stage, using a holistic approach aimed at grids to be flexible and resilient by design. Flexibility resources can also facilitate the restoration process by exploiting distributed black start capabilities including sector-coupling, which adds a new dimension to the necessary interactions pattern between electrical TSOs and DSOs, with utilities from other sectors. Power system planning for the future grid must embrace a wide range of network and non-network options to create operational flexibility options, including more active demand management techniques and customer-sensitive smart load shedding procedures.

The next level of flexibility is seen as being fully deployed and utilized for operation and planning of the power system, being integrated in procedures for long-term planning as well as in tools for stability support. The integrated dependency of flexibility directly impacts the resiliency of the power system, thus flexibility solutions intended to provide resilience support must be reliable and secure to provide the trust required for operation and planning.

Many of the worldwide ongoing initiatives, some of which presented in the Appendix, can provide highly relevant knowledge to the question of *How can flexibility support resilience? Indeed, they show the relevance and the potential values to be unlocked, with potentially some low hanging fruits to start with.* Some of the examined areas include:

System Integrity Protection Schemes (SIPS) are solutions found in power systems around the world which are used to mitigate large disturbances. Flexibility solutions, such as fast control of load and distributed generation, can be used to improving existing SIPS and enable development of new solutions, including: Controlled load-shedding, Islanding and island operation, Distributed recovery & black-start, and Emergency controls.

System Technical Performance can be improved through the use of flexibility solutions, where the resilience of the grid is increased. Flexibility solutions such as enabling of flexible transfer capacities and controllability of distributed assets support the resilience in the sense of: increased the number of mitigating measures based on the vast amount of controllable assets; improved performance regarding prevention of congestion, distributed voltage support, enhanced stability and reduced system losses; simplified maintenance planning as well as operational processes.

Alternative Grid Development, provide an agile and sustainable development of the power grid and can support power system resilience through: optimising the investment levels versus the operational costs, and secure solutions to defer investments enabling more efficient planning processes. With a regulation moving towards supportive of the total expenditure, alternative grid development solutions can become reality as both short- and long-term resilience enhancement solutions.
The economic value provided by large scale flexibility solutions, including reduced costs for security measures (e.g. redispatch), can increase the benefit of maintaining high levels of resilience and thus provide incentives for resilience-enhancing investments. Additionally, cyber security is an area with increased focus, where common platforms for data sharing and AI & machine learning solutions are part of the digitalisation of the power system. Finally, standardisation of solutions (architecture, tools, & platforms) is important to increase the reliability & acceptance in order for large scale deployment of flexibility.

Possibilities for future work

A distinctive value proposition would be to find break-even conditions among preventive, containment and restoration measures.

- ✓ Performing quantification value analysis, through a stochastic risk analysis approach for adopting resilience measures whose implementation cost is lower (in probabilistic terms) than the saved costs from system failure situations.
- ✓ Exploration of criteria and applications for defining the break-even decision between redundancy of investments/assets and acceptance of degraded service risk; for example, if flexibility from other sectors can provide fast and secure restoration, a higher LOLP can be accepted when planning the future system, with clear economic advantages.
- ✓ Elaboration of schemes for adaptive load shedding, based on market bids from end-users, extending the flexibility provision from the current limited use of “interruptible customers”. Transforming load shedding from a completely undesired action to a marketable option, increasing both customer savings and customer security of supply.
- ✓ Deepening of the evolution of TSO-DSO relations to include also joint planning and operation of resilience measures, beyond grid planning and coordinated operation.
- ✓ Further development of holistic solutions (e.g., *appendix 5 solutions*) to deploy and prove the concept of the system of system vision in the field.

8. LIST OF REFERENCES

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APPENDIX

In many countries around the world, power system engineers and scientists are working hand to hand on the R&D&I projects with aim to develop, test or adopt technologies that allows them to influence carbon emissions.
This section provides information and learning from projects and initiatives provided by the task force members from the ISGAN and ETIP-SNET communities, with details of each initiative provided in dedicated Appendices.
Here also we would like to thank the authors and contributors for sharing their research and technical knowledge on relevant opportunities and challenges, and for sharing and exploring the lessons learned from actual implementation, analysing on how to move the flexibility concepts forward to support the resilience of the power system.

List of projects:

A. FlexPlan Project

Project basic information

Main goal: The FlexPlan project aims at establishing a new grid planning methodology considering the opportunity to introduce new storage and flexibility resources in electricity transmission and distribution grids as an alternative to building new grid elements.
List of partners: RSE(Coordinator), EKC, KU-Leuven, N-SIDE, R&D NESTER, SINTEF, TECNALIA, TU-Dortmund, VITO, TERNA, REN, ELES, ENEL
Source of funding: European Union's Horizon 2020 research and innovation programme

Duration: 2019-2022

Webpage: https://flexplan-project.eu/

Project learnings

FlexPlan aims at providing the following contributions:

- development of a new methodology and of a new tool optimizing T&D planning by considering the placement of new storage devices as well as the flexible exercise of some loads in selected grid nodes as an alternative to traditional grid planning;
- application of this methodology to perform a grid planning analysis over six European regional cases by considering both the mid- and the long-term (2030, 2040, 2050) in one only optimization process. In addition, pan-European scenarios are run as well, in order to establish consistent border conditions for all 6 regional cases;
- elaboration of regulatory guidelines aimed at providing National Regulatory Authorities with indications on the opportune regulation to be adopted for maximizing the benefits that can be obtained with the new grid planning methodology. These guidelines will be built by considering the potential role of flexibility and storage as a support of T&D planning, resulting from the outcome of the six regional cases.

The following sections will first outline the main characteristics of the new grid planning methodology implemented by FlexPlan and then will concentrate on the modalities adopted to select technologies and characteristics of possible flexible resources (new storage and flexibilization of existing big loads) to be proposed to the grid planning procedure in alternative to build new lines or reinforce existing ones.

The innovative FlexPlan grid planning methodology. FlexPlan creates a new innovative grid planning tool whose ambition is to go beyond the state of the art of planning methodologies by including the following innovative features: assessment of best planning strategy by analysing in one shot a high number of candidate expansion options provided by a pre-processor tool, simultaneous mid- and long-term planning assessment over three grid years (2030-2040-2050), incorporation of full range of Cost Benefit Analysis criteria into the target function, integrated transmission distribution planning, embedded environmental analysis (air quality, carbon footprint, landscape constraints), probabilistic contingency methodologies in replacement of the traditional N-1 criterion, application of numerical decomposition techniques to reduce calculation efforts and analysis of variability of yearly RES and load time series through a Monte Carlo process.

The objective of the grid planning tool optimization is to maximize the system social welfare. This is obtained by minimizing the sum of T&D grid investments, operational costs bound to system dispatch and environmental impact costs, while maximizing the benefits achieved by the use of the flexibility sources and storage. To do so, it takes in input a large number of grid expansion and flexibility candidates and analyses them in order to quantify their costs. This is done by also taking into account environmental impact (air quality, life-cycle assessment and landscape). The obtained costs are included into the optimized objective function and the best trade-off between T&D system investments and operational costs is finally calculated (Figure 12).

The optimization is carried out in parallel for the three scenarios defined in the Ten-Year Network Development Plan by ENTSO-E (https://tyndp.entsoe.eu/tyndp2018/), whereas yearly climate variants are accounted for in the framework of a Monte Carlo process.

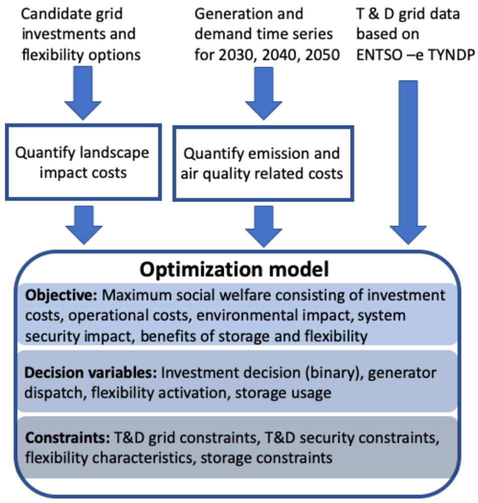


Figure 12- High level outline of the FlexPlan optimization model

The set of candidates to be provided in input to the planning tool (new lines/cables, storage elements, flexible exercise of existing big loads) is created by another tool called pre-processor. This second tool is particularly delicate because its responsibility is to provide a valid set of candidates in order to allow the planning tool to perform a really optimal selection. Unfortunately, unlike the planning tool, the pre-processor cannot be based on a clear-cut set of equations, but it needs to set up a heuristic technique. The true difficulty is to incorporate in this heuristics the know-how human grid planners dispose of.

The FlexPlan pre-processor. The FlexPlan pre-processor analyses both suitable line reinforcements (either cable or overhead lines) and suitable nodes for investing in new storage devices as well as in converting the way to manage big loads into a flexible one and ranks for each node the suitability of different kinds of investments by using the information provided by Lagrange multipliers of line transit constraints and nodal power balance of a non-expanded minimum cost OPF (see Figure 13) Lagrange Multipliers provide information on how much the target function would improve as a consequence of a unit relaxation of the constraint.

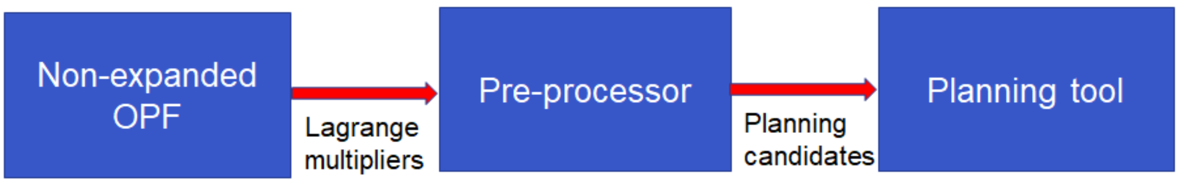


Figure 13 Pre-processor elaboration chain

As initially only information on non-expanded OPF at 2030 (the initial year of the simulation) is available, a iterative process is set up interweaving runs of the non-expanded OPF at the three grid years (2030, 2040 and 2050), runs of the pre-processor and runs of the planning tool (see Figure 14)

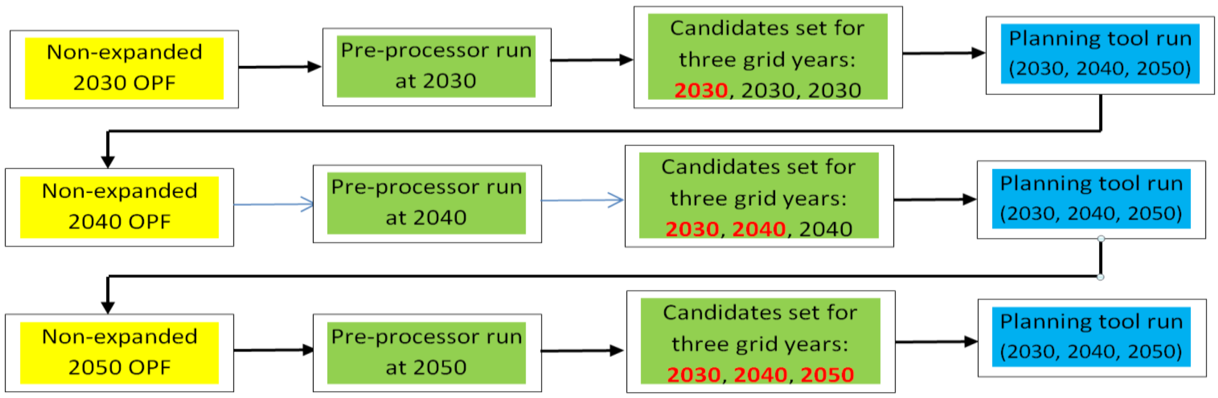


Figure 14 Pre-processor elaboration chain

Finally, determining expansion candidates by looking at Lagrange multipliers (LM) of line transit constraints generates the problem that by removing a congestion on a line, power flows increase and this could create congestion elsewhere (e.g. downstream in a tree-like topology). A specific procedure is adopted to clusterize lines which could saturate in cascade to create what is generically referred to as an expansion corridor.

The following sections deal with the process carried out by the FlexPlan pre-processor to select flexibility resources characteristics (technology, size and cost) by also considering the peculiarities of the locations where they should be inserted. Most of the information below is extracted from two deliverables of the FlexPlan project D2.2, which deals with the flexibility elements identification and characterization (available at https://flexplan-project.eu/publications/) and D2.3., which describes the methodology of the FlexPlan pre-processor (available in the following weeks at the same site). References for the information provided can be found at the reference documents.

Characterization of flexible resources (Ref. D.2.2). The technological maturity and the economic viability of flexibility technologies together with their increasing installed volume has reached a level which justifies that network planning activities no longer rely only upon reinforcements of the network infrastructure. Taking into account flexibility resources in network planning procedures and tools requires, however, significant reformulations to accommodate for the uncertainties and the specific characteristics of such technologies. Depending on the specific network challenges addressed by the planning tools, proper simplified models and acceptable level of aggregated considerations need to be carried out.

In the FlexPlan project approach, two main resources are proposed as flexibility providers for the network and included in the network planning process: Storage and Demand Response. For each of them, the characteristics of specific technologies have been analysed: batteries, demand response (flexible loads), electric vehicles, hydrogen storage, pumped storage hydro, thermal loads, Combined Heat and Power (CHP), Compressed Air Storage (CAES), Liquified Air Energy Storage (LAES) and thermoelectric storage. The mainly considered aspects are flexibility capabilities, technology maturity, costs and environmental impact. A flexibility potential assessment was carried out including a review of the typical values of the main parameters for each of the technologies. The process resulted in a selection of flexibility technologies to be considered in FlexPlan.

Below, different techno economical characteristics of the flexibility resources are detailed. The possible value ranges are presented in qualitative manner to allow a comparison between different flexibility options. The values are provided in ranges due to many factors, for example the capital expenditure varies widely between different countries and regions. However, the pre-processor tool can select specific values depending on location characteristics.

Power capacity. In conventional planning, power capacity means, meeting peak demand with the net generation. The objective of considering the flexibility resources in planning is to avoid oversizing the network, for a rarely occurring peak demand, and to support the fluctuations in RES generation and demand variation. In this perspective, the power capacity of the flexibility resources must be capable to provide network services during the hours of generation consumption imbalances, congestion and voltage deviation. The following table provides a qualitative indication of power capacity of different flexibility resources.

Table 1 Power capacity range for different flexibility resources

Flexibility resource		Power Capacity Range
Battery energy storage system (Electricity Storage and Renewables: Costs and Markets to 2030, 2017), (enea-Consulting, 2012) (Sabihuddin, Kiprakis, & Mueller, 2015)		kW - MW
Demand Response (COWI-CONSORTIUM, 2016),	Domestic	kW
	Industrial	kW-MW
Electric vehicles (IRENA, 2019)		kW-MW
Hydrogen (IEA, The Future of Hydrogen Report Seizing today's opportunities, June 2019), (Leeuwen & Zauner, February 2020)	Alkaline	kW-MW
	PEM	kW-MW
	SOEC	kW-MW
Pumped Hydro		MW
Thermal loads (Baetens, 2016)	Space Heating/Cooling	kW-MW
	Cold storage	MW
Combined heat and power (Bhandari, et al., 2018), (Lazzarini, Aluisio, & Falorni, 2018), (Lund & Andersen, 2005)		kW-MW
Compressed air storage (Wang, Wang, Wang, & Yao, 2013)		kW-MW
Liquid-Air Electricity Storage systems (Highview Power, u.d.)		kW-MW
Thermo electric storages		kW-MW

In conventional planning, energy capacity in generation units are considered to meet average demand in a year. The primary source of supply (fuel) is continuous and sufficient to meet the average demand except during the planned and unexpected outage periods in which the backup resources may become necessary. In the case of flexibility resources, one of the important characteristics which decides the duration of flexibility service at the desired power rate is their energy capacity.

Table 2 Energy capacity range for different flexibility resources

Flexibility resource	Energy capacity range
Battery energy storage system (Electricity Storage and Renewables: Costs and	kWh to MWh

Markets to 2030, 2017), (enea-Consulting, 2012), (Sabihuddin, Kiprakis, & Mueller, 2015)		
Demand Response	Domestic	kWh to MWh
	Industrial (Starke & Alkadi, 2013)	kWh to MWh
Electric vehicles (IRENA, 2019)		kWh to MWh
Hydrogen (IEA, The Future of Hydrogen Report Seizing today's opportunities, June 2019), (Leeuwen & Zauner, February 2020)		MWh
Pumped hydro		TWh
Thermal loads	Space heating /cooling	kWh to MWh
	Cold storage	MWh
Combined heat and power (Bhandari, et al., 2018), (Lazzarini, Aluisio, & Falorni, 2018), (Lund & Andersen, 2005)		kWh to MWh
Compressed air storage (Wang, Wang, Wang, & Yao, 2013)		MWh
Liquid-Air Electricity Storage systems (Highview Power, u.d.)		MWh
Thermo electric storages		MWh

The larger the energy capacity of the flexibility resource, the larger the duration for which flexibility can be activated to provide network services. At the same time, the served flexible energy will be harvested back by the flexibility resources from the same network. As FlexPlan considers the service duration of minimum period of 1 hour, the flexibility resources which can provide flexibility only for less than hours are not considered. Table 3 provides a qualitative indication of energy capacity of different flexibility resources considered for analysis.

Response time. Response time describes, how fast the flexibility resource can adjust its consumption to the flexibility activation signal (Akrami, Doostizadeh, & Aminifar, 2019), (Holttinen, Tuohy, Milligan, & Lannoye Vera Silva, 2013). Response time of the flexibility resource is one of the important parameters to be considered. Some flexibility resources cannot be activated as and when needed though they have high flexibility potential. For example, industrial demand response potential is associated with the processes in the specific industry which may not be interrupted once started. A prior planning is needed for activation. On the other hand, flexibility resources like BESS can respond to activation in very short time (in seconds). Another perspective is long term impact of flexibility activation. For example, flexibility activation on pumped hydro power plants will affect their capacity in long term, if the planning is not considered (Akrami, Doostizadeh, & Aminifar, 2019). Table 3 lists response time of different flexibility resources in qualitative manner.

Table 3 Flexibility activation response time range for different flexibility resources

Flexibility resource		Response time
Battery energy storage system (Sabihuddin, Kiprakis, & Mueller, 2015)		seconds
Demand Response (COWI-CONSORTIUM, 2016)	Domestic	seconds to hours
	Industrial	Hours to days
Electric vehicles (IRENA, 2019)		Seconds to hours
Hydrogen (IEA, The Future of Hydrogen Report Seizing today's opportunities, June 2019), (Leeuwen & Zauner, February 2020)	Alkaline	Hours
	PEM	Hours
	SOEC	Hours
Pumped hydro		Hours to days
Thermal loads (Baetens, 2016)	Space heating /cooling	Seconds to hours
	Cold storage	minutes
Combined heat and power (Bhandari, et al., 2018), (Lazzarini, Aluisio, & Falorni, 2018), (Lund & Andersen, 2005)		minutes
Compressed air storage (Wang, Wang, Wang, & Yao, 2013)		minutes
Liquid-Air Electricity Storage systems (Highview Power, u.d.)		Hours
Thermo electric storages		minutes

Payback time. The flexibility activation will alter the power consumption. The change may reduce or increase the energy demand in the flexibility activation duration. In the case of DR programs, the energy consumption reduced must be paid back. For example, if an EV charging power is reduced to manage congestion in the network, the charging duration to serve scheduled energy delivery will increase. Also, this energy must be delivered before the EV is disconnected from the charge post. The disconnection time is not elastic. The time between the flexibility activation and EV disconnection time is the payback time. Similarly, for BESS, the batteries must be charged/discharged back to prepare them for next flexibility activation. The typical full cycle usage time of the BESS is its payback time. The following table gives a qualitative indication of payback time of different flexibility resources. (Hydrogen generation is considered as industrial DR).

Table 4 Energy payback time range for different flexibility sources

Flexibility resource	Payback time

Battery energy storage system		6 – 8 hours
Demand Response	Domestic (COWI-CONSORTIUM, 2016)	1 - 24 hours
	Industrial (COWI-CONSORTIUM, 2016), (Starke & Alkadi, 2013)	1 - 12 hours
Electric vehicles (IRENA, 2019)		1 – 8 hours
Hydrogen	Alkaline	Within 24 hours
	PEM	Within 24 hours
	SOEC	Within 24 hours
Pumped hydro		**
Thermal loads (COWI-CONSORTIUM, 2016)	Space heating /cooling	1 - 12 hours
	Cold storage	1 - 12 hours
Combined heat and power		**
Compressed air storage		Within 6 hours
Liquid-Air Electricity Storage systems (Highview Power, u.d.)		< 6 hours
Thermo electric storages		< 2hours

***Not Applicable

Physical constraints. For flexibility technologies being considered as alternative solutions in the network planning process, the geographical and environmental limitations have paramount importance. This will be the case when a flexibility resource is the theoretical optimum solution at a specific location while requirements regarding to the land area or lack of other resources in the surrounding area makes it infeasible. Hence, overview of the requirements for the physical placement of certain flexibility resources is presented in Table 5 to screen out infeasible alternatives.

Table 5 Energy density and site dependency for different flexibility resources

Flexibility resource		Energy density (kWh/m^3)	Site dependencies
Battery energy storage system (Electricity Storage and Renewables: Costs and Markets to 2030, 2017)		10.5 - 500	Sufficient space for battery pack placement near the substation.
Demand Response	Domestic	**	Presence of residential and industrial customers and their willingness.
	Industrial	**	
Electric vehicles (IEA, Global EV Outlook 2018 - Towards cross-modal electrification, 2018)		200 - 300	Presence of public/ private charging infrastructures and their willingness.
Hydrogen (EASE Energy Storage Technology Descriptions, u.d.)	Alkaline	30 -2550	Presence of industrial customers and their willingness.
	PEM	30 -2550	
	SOEC	30 -2550	
Pumped hydro (Electricity Storage and Renewables: Costs and Markets to 2030, 2017)		1 -2	Availability of river inflow, geographical terrain with differential head, and political and environmental clearance.
Thermal loads	Space heating /cooling	**	Presence of residential and industrial customers and their willingness.
	Cold storage	**	
Combined heat and power		**	Geographical land potential and accessibility to fuel supply and heat despatch. Environmental regulations.
Compressed air storage (Electricity Storage and Renewables: Costs and Markets to 2030, 2017)		3 - 6	Geographical accessibility of large underground cavities and rock structure
Liquid-Air Electricity Storage systems (EASE Energy Storage Technology Descriptions, u.d.)		32 - 230	Sufficient space for Liquid-Air Electricity Storage systems.
Thermo electric storages (Sabihuddin, Kiprakis, & Mueller, 2015)		25 - 300	Presence of industrial customers and their willingness.

Technology maturity. Some of the flexibility resources are not off the shelf usable today. There are cost and technological barriers. For example, hydrogen generation by PEM is costly method as hydrogen generation by methane (natural gas) cracking process is low-cost method today. Similarly, SOEC method of hydrogen generation is not at industry scale as electrode corrosion is big technological barrier today. However, the flexibility resources like DR are seeing visibility in the network as barriers for full scale implementation due to lack of sensors and measurements and data availability. The following table lists the present and expected status of technological maturity of different flexibility options and their barriers.

Table 6 Technology maturity of different flexibility resources at different time horizon

Flexibility resource		Technology maturity		
		2020	2030	2050
Battery energy storage system (Electricity Storage and Renewables: Costs and Markets to 2030, 2017), (enea-Consulting, 2012), (Sabihuddin, Kiprakis, & Mueller, 2015)				
Demand Response (Final Report: Demand Side Flexibility Perceived barriers and proposed recommendations, 2019)	Domestic	Sensor, ICT and data visibility		
	Industrial	Sensor, ICT and data visibility		
Electric vehicles (Final Report: Demand Side Flexibility Perceived barriers and proposed recommendations, 2019)		Sensor, ICT and data visibility		
Hydrogen (IEA, The Future of Hydrogen Report Seizing today's opportunities, June 2019), (Leeuwen & Zauner, February 2020)	Alkaline			
	PEM	Lab/Pilot	Cost	
	SOEC	Cost and technology (Lab scale)	Electrode Corrosion issue	Cost
Pumped hydro				
Thermal loads (Baetens, 2016)	Space heating /cooling	Pilot scale		
	Cold storage	Pilot scale		
Combined heat and power (Bhandari, et al., 2018), (Lazzarini, Aluisio, & Falorni, 2018), (Lund & Andersen, 2005)				
Compressed air storage (Wang, Wang, Wang, & Yao, 2013)				
Liquid-Air Electricity Storage systems (Highview Power, u.d.)		Cost		
Thermo electric storages		Cost		

Cost. Therefore, the CAPEX and OPEX and calculated for in terms of kW/year. European commission DG Energy report on "Impact assessment study on downstream flexibility, price flexibility, demand response & smart metering" analyses the different demand scenarios, network reinforcement cost, DR potential and prescribes CAPEX and OPEX for DR (COWI-CONSORTIUM, 2016). The resources which the power and energy capacity are independent of each other, for example pumped hydro storage, hydrogen, compressed air storage, liquid-air electricity storage and thermo electric storages CAPEX and OPEX are considered for their power rating. Their storage cost depends on different parameters. For example, storage cost for hydrogen is calculated in terms of cost per kWe, kWh, kg of hydrogen or m^3 of hydrogen, see table 7 and table 8.

Table 7 CAPEX range for different flexibility resources at different time horizon

Flexibility resource		CAPEX (€/kW(h))		
		2020	2030	2050
Battery energy storage system (Electricity Storage and Renewables: Costs and Markets to 2030, 2017), (Sabihuddin, Kiprakis, & Mueller, 2015), (Cole & Frazier, June 2019)		278 - 1475	95 - 505	67 - 226
Demand Response (COWI-CONSORTIUM, 2016)	Domestic	54/year	29/year*	15/year*
	Industrial	54/year	29/year*	15/year*
Electric vehicles (COWI-CONSORTIUM, 2016)		54/year	29/year*	15/year*
Hydrogen (IEA, The Future of Hydrogen Report Seizing today's opportunities, June 2019), (Leeuwen & Zauner, February 2020)	Alkaline	0.5 k – 1.5 k	0.3 k - 0.7 k	0.2 k- 0.6 k
	PEM	1.2 k – 1.8 k	0.6 k – 1.4 k	0.2 k – 0.8 k
	SOEC	2.5 k - 5 k	0.7 – 2.5 k	0.5 k – 0.9 k
Pumped hydro		40 -150	21.5-80.8*	16-43.5*
Thermal loads (Baetens, 2016)	Space heating /cooling	54/year	29/year*	15/year*
	Cold storage	54/year	29/year*	15/year*
Combined heat and power (Teske, 2019)		0.88 k – 2.244	0.88 k – 2.155	0.88 k – 2.068

	k	k	k
Compressed air storage (Electricity Storage and Renewables: Costs and Markets to 2030, 2017), (Vafeas, Pagano, & Peirano, 2014)	40-80	40-80	40-80
Liquid-Air Electricity Storage systems (Highview Power, u.d.)	60 - 600	32.3-323*	17.4-174*
Thermo electric storages			

*values are calculated by taking discount rate of 6% per year as recommended by (The social discount rate, 2012)
(Value at year 'n'= Value at year '1' x (1- discount rate/100)^n

Table 8 OPEX range for different flexibility resources at different time horizon

Flexibility resource		OPEX(€/kW(h))		
		2020	2030	2050
Battery energy storage system (Electricity Storage and Renewables: Costs and Markets to 2030, 2017), (Sabihuddin, Kiprakis, & Mueller, 2015) (Vafeas, Pagano, & Peirano, 2014)		Very Small	Very Small	Very Small
Demand Response (COWI-CONSORTIUM, 2016)	Domestic	32/year	17.2/year¤	9.2/year¤
	Industrial	32/year	17.2/year¤	9.2/year¤
Electric vehicles (COWI-CONSORTIUM, 2016)		32/year	17.2/year¤	9.2/year¤
Hydrogen (IEA, The Future of Hydrogen Report Seizing today's opportunities, June 2019), (Leeuwen & Zauner, February 2020)	Alkaline	2 % of CAPEX	2 % of CAPEX	2 % of CAPEX
	PEM	2 % of CAPEX	2 % of CAPEX	2 % of CAPEX
	SOEC	2 % of CAPEX	2 % of CAPEX	2 % of CAPEX
Pumped hydro		Small	Small	Small
Thermal loads	Space heating /cooling	32/year	17.2/year¤	9.2/year¤
	Cold storage	32/year	17.2/year¤	9.2/year¤
Combined heat and power (€/kW(h)) * (Teske, 2019)		0.01 -0.039	0.013 -0.068	0.017 -0.11
Compressed air storage (Wang, Wang, Wang, & Yao, 2013),		0.15 – 0.30	0.15 – 0.30	0.15 – 0.30
Liquid-Air Electricity Storage systems		Small	Small	Small
Thermo electric storages				

*Fuel cost,
¤values are calculated by taking discount rate of 6% per year as recommended by (The social discount rate, 2012)
(Value at year 'n'= Value at year '1' x (1- discount rate/100)^n

Environmental impact. One of the ways to measure the environmental impact of different flexibility resources is by CO_2 emission on flexibility activation. A detailed analysis of CO_2 emission for different battery technologies based on life cycle analysis is presented in (Sabihuddin, Kiprakis, & Mueller, 2015) and compared with other energy storage technologies. Similarly, CO_2 emission due to domestic DR is presented in (McKenna & Darby, 2017). The indicative values of CO_2 emission on flexibility activation on different resources are listed in table 9.

Table 9 Emission in Kg of CO2 / kWh for different flexibility resources

Flexibility resource		kg of CO_2/kWh
Battery energy storage system (Oliveira, et al., 2015) (Sabihuddin, Kiprakis, & Mueller, 2015)		0.02 to 0.1
Demand Response	Domestic (McKenna & Darby, 2017)	0 to 1.9
	Industrial	**
Electric vehicles (Vafeas, Pagano, & Peirano, 2014)		0.275 – 0.375
Hydrogen (Sabihuddin, Kiprakis, & Mueller, 2015) (Oliveira, et al., 2015)	Alkaline	< 0.01
	PEM	< 0.01
	SOEC	< 0.01
Pumped hydro (Sabihuddin, Kiprakis, & Mueller, 2015) (Oliveira, et al., 2015)		< 0.01
Thermal loads	Space heating /cooling	**
	Cold storage	**
Combined heat and power (Combined Heat and Power , u.d.), (Cogeneration, or Combined Heat and Power (CHP), u.d.)		0.45 – 0.75
Compressed air storage (Sabihuddin, Kiprakis, & Mueller, 2015) (Oliveira, et al., 2015) (Vafeas, Pagano, & Peirano, 2014)		0.2-0.285

Liquid-Air Electricity Storage systems	**
Thermo electric storages	**

** Not applicable or no data available.
For the characterization of the specific technologies, check D.2.2 of FlexPlan.

Modelling of flexible resources (Ref. D.2.2). Technologies identified as flexibility resources have their own technical characterizing parameters. These parameters are essential in the development of models representing them in the formulations of the network planning tool. The level of detail of the characterizing parameters is highly dependent on the level of dynamics one set to represent during the operations of the technologies. In FlexPlan planning tool, decisions are made for a 1-hour time resolution analysis for primary flexibility service of congestion management. Accordingly, individual characterizing parameters for the selected flexibility technologies are presented. Some of the parameters are to be decided in the planning tool while other characterizing parameters are to be represented by typical values. Two generic groups are developed for the modelling purposes based on similarities of the characteristics of the resources. The two generic groups are storage group and demand response group:

- **Storage** modelling: reservoir and pumped hydro, batteries, CAES, LAES, hydrogen storage, thermo-electric storage.
- **Demand Response** modelling: EVs, Industrial/Residential/Commercial loads, hydrogen production as industrial load.

As input for the modelling, four types of information are considered:

- **Sets**: they deal with planning horizons, periods in the planning horizon and storage/flexible demand element and, in the case of flexible demand, the time windows.
- **Variables**: they define the status of the resource, mainly, power injected or absorbed and capacity level in the case of storage; and, in the case of flexible demand, power consumption, not consumed power and upward/downward demand shifted.
- **Parameters**: they define the characteristics of a technology, mainly, rated power, rated capacity, maximum and minimum operation levels, initial energy level, efficiency, ramps characteristics, etc. in the case of storage; and, in the case of flexible loads, reference demand, maximum upward/downward shift of demand, grace period for upward/downward shifting, etc.
- **Constraints**: relationships between variables and parameters are established to represent the constraints related to the storage and flexible loads e.g., energy balance constraints, maximum and minimum energy capacity constraints, load shifting capacity, etc.

The following figures show graphically the models of both storage and flexible loads (related to demand response strategies).

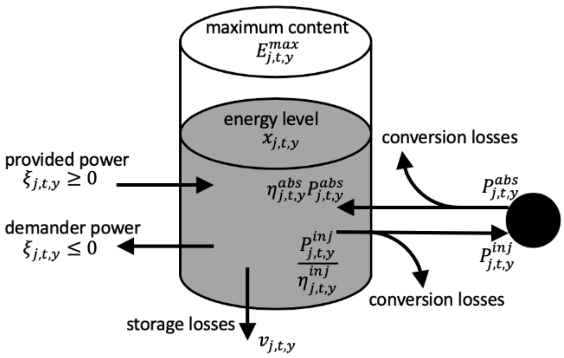


Figure 15 Dynamic of storage

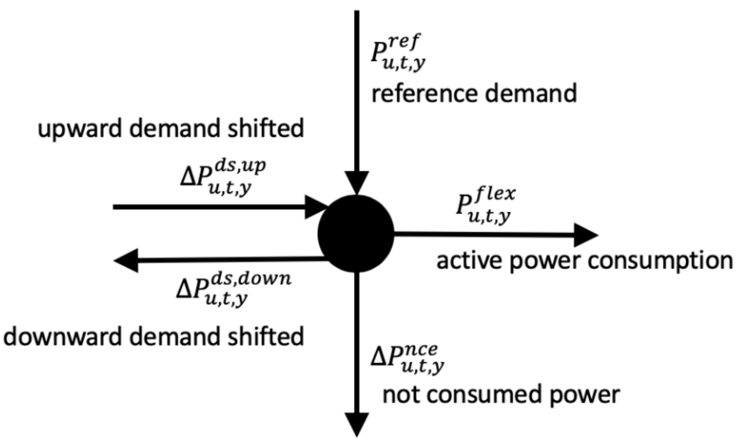


Figure 16 Flexible node balance.

For more details on the modelling of storage and flexible loads, check D.2.2 of FlexPlan.

Flexibility candidates preselection for network planning (Ref. D2.3). To support the planning process, the FlexPlan project develops a specific software tool which performs a pre-selection of candidates for network expansion. Such tool acts as a pre-processor of the planning tool, and its main objective is to restrict the number of possible network expansion options and, in this way, limit the size of the optimisation problem to be solved.

The flexibility resources analysis is performed through the following steps:

- Network branches potentially affected by congestion are identified on the basis of an optimal power flow (OPF) simulation carried out on a network characterised by the final generation and load scenario for the target year under study (2030, 2040 or 2050), but still before new grid investments are carried out. A ranking of congested lines is proposed based on Lagrange multipliers' (LM) values associated to transit constraints equations for the system tie-lines.
- Subsequently, a "corridor analysis" is carried out to avoid that expanding the lines located with the procedure of the previous bullet just shift congestion to some other line of the network. This analysis is done by considering the so called Power Transfer Distribution Factors (PTDF), which provide a linearized description of active power flows in the network.
- The flexibility resources analysis tool (pre-processor) proposes a list of network expansion candidates, including storage, demand response (DR), phase-shifting transformers (PSTs) and lines/cables/transformers, to solve congestion in the identified branches. This selection is performed based on congestion characteristics and on possible location-related constraints. Cost and size details are provided related to the technology of each selected candidate.
- Eventually, the proposed candidates for grid congestion support are provided to the planning tool as input, which, in turn, assesses the best planning option for the power system in the time frame of the study.

The following Figure 6 summarises graphically the steps carried out by the pre-processor in relation with the planning tool.

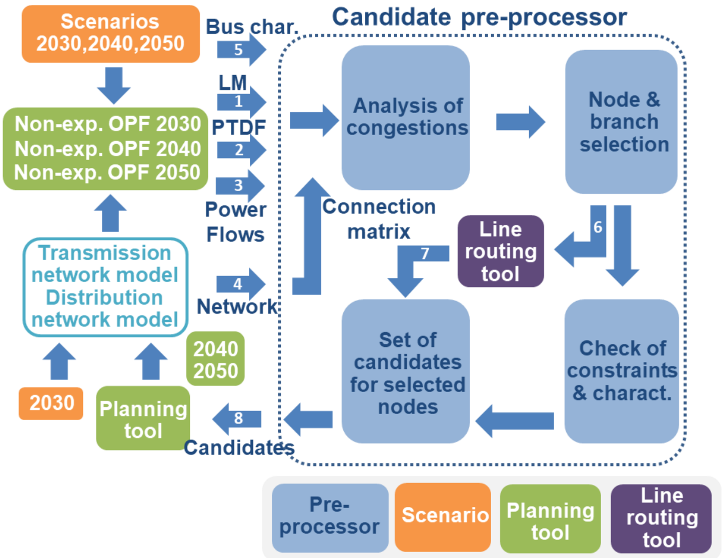


Figure 17 Pre-processor tasks in relation to FlexPlan planning methodology

As starting point, an OPF of the non-expanded network is carried out by the OPF module included in the planning tool software suite. As a result of this, Lagrange Multipliers (LM), Locational Marginal Prices (LMP) and Power Transfer Distribution Factors (PTDF) values are provided to the candidates' pre-processor. In addition to this, the pre-processor also takes as input the network model and the bus characterization performed by the user and included in the grid model data format. With these inputs, the main steps of pre-processor are carried out: first, the analysis of congestions and the selection of the nodes and branches that need to be upgraded; second, the check of location constraints and congestion characteristics; third, the pre-selection of a set of candidate technologies, including cost and size. In this last case, an additional tool, the line routing tool, is used to provide line candidates between to nodes or substations. Pre-selected candidate technologies are handed over to the planning tool, which performs the optimization and selects among them, those that provide, altogether, a best network expansion solution. This is performed in loop, for the three time frames 2030, 2030-2040, 2030-2040-2050.

The two main tasks that are carried out by the pre-processor to perform the flexibility resources candidate's preselection are the following:

- Selection of congestion scenarios.
- Selection of candidates.

Selection of congestion scenarios

There are two main inputs to perform the selection of congested scenarios:

- **Optimal Power Flow (OPF).**
- **Transmission and distribution networks models and scenarios.**

The non-expanded OPF module run within the planning tool suite first performs an OPF for the non-expanded network for years 2030, 2040 (including a trial expansion in 2030) and 2050 (including a trial expansion in 2030 and 2040)[67]. Four types of inputs are provided by the planning tool at this stage: The Locational Marginal Prices (LMPs), the Lagrange Multipliers (LM), Power Transfer Distribution Factors (PTDF) and the power flows in the branches of the system.

Lagrange Multipliers of lines transit constraints (LM) are a direct outcome of the solution of the optimization problem (OPF). They provide information about the dispatching cost reduction deriving from sending an additional MW of power through a branch. Therefore, they permit to identify congested lines: these lines will be characterized by non-zero LM value and such value will correspond to the dispatching cost reduction deriving from a unit increase of the line transit limit.

Locational Marginal Prices (LMP) show the dispatching cost variation to accommodate a unit increment of demand at a bus. They provide useful information for the location of flexible resources (storage and DR).
We could say that the LMs represent the value of the interconnection capacity of the corresponding line and the LMPs the value of energy in the corresponding node.

Power flow values of branches provide information about the direction of the flow of energy and about their saturation level, in relation to their rating.
In a year-long simulation, the OPF provides a value for all these three parameters for each of the 8760 hours and for each of the buses and branches.

The **Power Transfer Distribution Factors** (PTDF) matrix represents the change in the active power flow through a network branch as a consequence of a unit extra injection in a given system node. This information is dependent on the topology and, therefore, it is considered constant for one year of study.

The **topology of the network** provides the relationship between buses and branches and the characteristics of network elements (the power rating of the branches, electrical characteristics of network assets…). The overall network model includes transmission, sub-transmission and distribution networks models.

Selection of candidates. The selection of candidates is mainly linked to the relief of the congestion constraints. Therefore, a set of candidates is proposed for each of the congestion scenarios identified at the previous step, which are related to a specific location in the network.
Together with storage and demand response, conventional grid assets for network extension are provided as candidate for the planning tool to choose the best option through the optimization process. The flexibility candidates considered by the tool are the following:

- **Storage:** batteries (lithium ion, NaS and flow), hydrogen, hydro, compressed air storage (CAES) and liquid air storage (LAES).
- **Demand Response (DR):** through flexible loads.
- **Conventional network assets:** lines/cables (AC&DC) and transformers.
- **Phase-Shifting Transformers (PSTs).**

All the technologies above are considered as possible candidates for network extension. However, for all locations where a congestion is identified, the suitability of each technology is checked through the analysis of local constraints and the characteristics of the congestion. The selection of candidates at a specific node or branch is screened according to this characterization: the network information provided for nodes is used to discard, or not, some of the candidate technologies.

In order to process these characteristics automatically, a heuristic approach is assumed to check the constraints and network characteristics at different levels:

- **Location constraints:** the grid model allows the characterization of network nodes to include existing constraints. These are the characteristics that can be assigned to each network node or bus (underlined are the ones used in the current version of the tool):
- **Type of bus**: <u>substation</u> (air, air-compact, underground); <u>Industrial load</u> (metal, paper, textile, cement, water treatment, gas industry, mining, shipyard, high speed train, automotive, chemical, other); <u>power plant</u> (wind, PV, solar, thermal coal, CC, biomass, <u>hydro</u>, nuclear); <u>commercial load</u> (airport, other).
- **Availability of natural resources** (for substation type buses): <u>water</u> (river, reservoir, if no hydro power plant is present); wind (area with wind parks near); sun (solar power plants near); <u>cavern</u>; biomass.
- **Loads supplied** (for substation type buses): residential (mainly); commercial (mainly); industrial (mainly); mixed (lower voltage level networks, sub-transmission/distribution); big industrial (as above, indicate main type/s).
- **Location of bus**: <u>urban</u> (populated city); <u>industrial</u> area; semi-rural (outskirts of populated city, small city); <u>rural</u>.
- **Geographic characteristics** (for rural buses): <u>mountainous</u>; <u>plain</u>
- **Restricted area** (not allowed to build new installations): for <u>lines</u>; for <u>hydro plants</u>; for <u>hydrogen</u>; for <u>batteries</u>; for <u>CAES/LAES</u>; <u>total</u>

[67] Each time the planning tool calculates a full set of expansions for the three years: 2030, 2040 and 2050

restriction.

- **Is interconnection:** if certain bus is connected to a bus in another country/region, it is considered suitable to install a PST.
- **Existence of industrial load at a selected node:** it allows to propose DR candidates among the large loads in the system.
- **Congestion characteristics:** the characteristics of the congestion, such as the number of congestion hours in one year or the number of consecutive congestion hours, make some candidate technologies more appropriate than others to solve them: e.g., if congestion tends to last more than six hours, batteries or demand response strategies might not be the best flexibility candidates. These rules are also implemented in the pre-processor tool.

To characterise the location, a list of codes is available for buses description. This information is introduced in the Grid Model Input File of the planning tool. If no information is provided no restriction is considered. After the characterisation of the nodes has been performed, the rules affecting the constraints need to be pre-defined.

Once the most suitable technologies have been selected for a location, the pre-processor provides a size and cost for each of them. In the case of the lines, an external software for line routing between two nodes is used to identify the characteristics and cost of both AC and DC candidate lines.

A second path for candidate pre-selection is through the direct proposal candidates by the user of the planning tool (in the frame of the project these would be Regional Case Leaders). The users need to provide a *from* and *to* nodes, indicating the branch they would like to assess from the congestion point of view in the system. At this moment, this is used for nodes that do not have a direct connection in the non-expanded grid model and that the user would like to consider as candidate options, since the candidates' pre-processor does not take into account this casuistry (no LM information would be available from the OPF).

Outputs from the pre-processor

The outputs from the process of the selection of candidates are handled over to the FlexPlan planning tool. According to the methodology, this below is a summary of the most relevant information provided by the flexibility candidates' tool to the planning tool:

- A **location** in the network (bus/branch id.) for the flexibility resource.
- A **list of candidate flexibility resources** for each location is selected among the following: storage, flexible loads (leading to DR strategies through existing load shifting or/and reduction), Phase Shifting Transformer (PST) and line (AC, both overhead and cable, HVDC).
- A **size** for each candidate: an approximate size for each technology is provided. In the case of flexible loads, a load reduction percentage capability is indicated. This reduction is by default related to a shift of load, in the industrial and commercial sectors, which means that this reduction will have to be compensated in the next hours to be able to provide the same service.
- A **cost** for each candidate: CAPEX or CAPEX and OPEX per power is provided (operation and maintenance costs, not related to the fuel or dispatching costs), depending on the type of technology (according to its definition in the optimization problem, WP1). The information comes from.

B. Coordinet Project

Project basic information

Main goal: The purpose of CoordiNet is establish different collaboration schemes between transmission system operators (TSOs), distribution system operators (DSOs) and consumers to contribute to the development of a smart, secure and more resilient energy system. Special emphasis will be on the analysis and definition of flexibility in the grid at every voltage level ranging from the TSO and DSO domain to consumer participation.

Source of funding: European Union's Horizon 2020 research and innovation programme

Duration: 2019-2022

Webpage: https://coordinet-project.eu/

Project learnings

The CoordiNet project is a response to the call LC-SC3-ES-5-2018-2020, entitled "TSO – DSO – Consumer: Large-scale demonstrations of innovative grid services through demand response, storage and small-scale generation" of the Horizon 2020 programme. The project aims at demonstrating how Distribution System Operators (DSO) and Transmission System Operators (TSO) shall act in a coordinated manner to procure and activate grid services in the most reliable and efficient way through the implementation of three large-scale demonstrations.

Objectives of the project.

The project has the main objective to demonstrate to what extent DSOs and TSOs, acting in a coordinated manner, can provide favourable cooperation conditions to all actors while removing barriers to participation for customers and small market players connected to distribution networks. CoordiNet has also developed new mechanisms, which are more suitable for real-time operations, to define requirements for the development of European standard flexibility platforms, Figure 1. To achieve such goals, the Coordinet project has focussed on the following concrete objectives:

1) The project has defined a set of standardized grid services for TSO-DSO needs. This objective was achieved with the participation and consensus of all the system operators participating in the project by defining in detail all the products and services that could be traded in the flexibility markets.

2) Different coordination alternatives between TSOs and DSOs were defined to make flexibility markets both possible and coherent, taking into account various possible scenarios. Seven possible coordination schemes resulted from the analysis and large-scale pilots developed in the three countries involved (Spain, Greece and Sweden) were intended to address the maximum number of conceptual possibilities. In each demo activity, different products have been tested, in different time frames and relying on the provision of flexibility by different types of Distributed Energy Resources (DERs).

3) To develop the aforementioned pilots, the project developed specific platforms to implement the exchange of information and interaction between TSOs, DSOs, market participants and aggregators, and to coordinate the different functions necessary to perform. The project also carried out market algorithms to select the most efficient outcomes. The first demo run has already been completed in all three countries and the results are being published on the CoordiNet website.

4) For the remainder of the project, all the planned tests, as well as the technical and economic analysis and the analysis of scalability and replicability will be finally performed. Having created an agile and robust operation system environment, the efficient economic signals and regulatory conditions for the applicability of these solutions need to be in place. The economic incentives need to be clearly set for all agents, including the DSO, TSO, flexibility service providers, etc.

Example. The conditions for the Spanish demo. Three system operators were involved in the project:

- TSO. Red Eléctrica de España (REE), is the system transmission network operator and owner of the transmission grid. REE, among other activities, is in charge of solving technical restrictions of the system and keeping the system balance. To perform these tasks, REE runs different ancillary service markets which include a congestion management market to solve the possible technical problems coming from the day-ahead energy market. In this technical congestion management market, which is only open for generators, participants are remunerated following the pay-as-bid system.
- DSOs. In Spain, DSOs own and operate the distribution network including 110 kV and below. Spain has six big distribution companies with more than 100.000 customers and more than three hundred distribution companies with less than 100.000 customers, The two biggest distribution companies participating in the CoordiNet Spanish demo are i-DE and e-distribucion. The Spanish demonstrators include distributed resources connected to the networks of both companies. The resources connected to i-DE's network are:

- Municipality buildings (significant demand loads) in Murcia province.
- Industrial load of a cement factory in Alicante province.
- Several facilities with renewable capacity in Murcia and Albacete provinces.

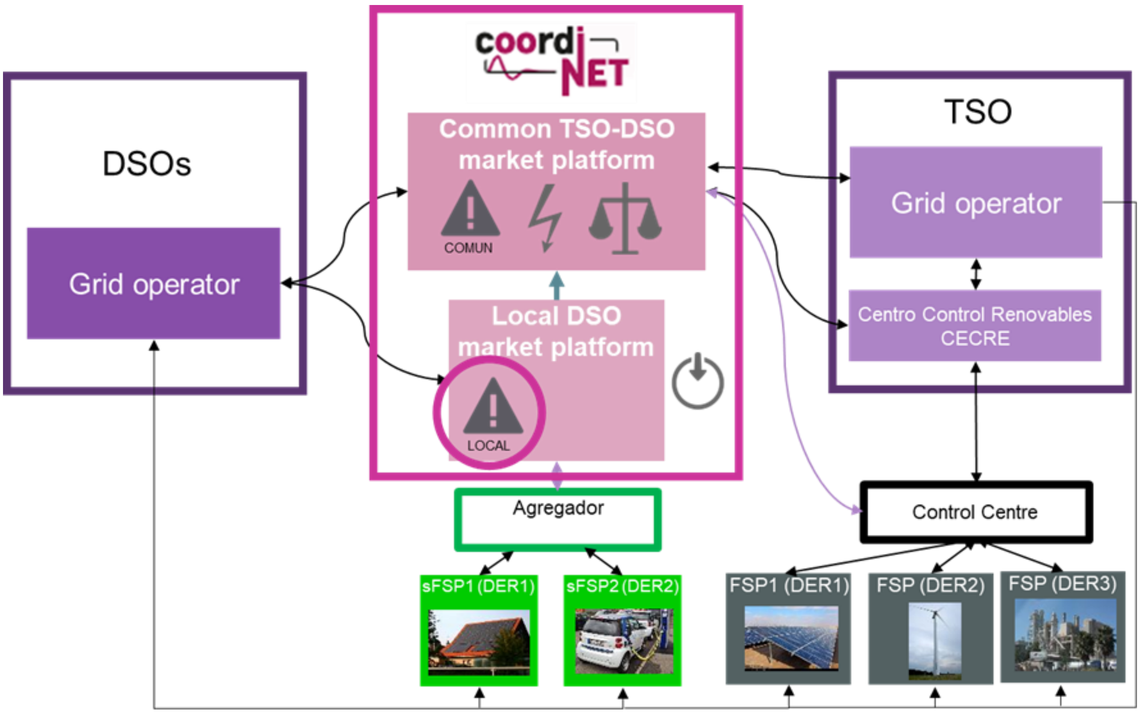


Figure 18 Platform scheme for the Spanish demo.

And the resources connected to Endesa's network are:

- Demand-side response from municipality buildings, cogeneration, biogas unit and generation resources from small wind and solar plants will provide flexibility for congestion management in Malaga province.

- Wind and solar photovoltaic (PV) will participate in congestion management and voltage control in Cadiz province.

The main objective of the congestion management use case is to procure flexibility from resources connected at both TSO and DSO networks in a coordinated manner to solve temporal congestions that can occur at both networks. Currently in Spain, the TSO manages network congestions that occur both at transmission*, and the DSO at the distribution grid level*. This is done through a technical constraint management market by re-dispatching generation units connected at transmission, but also at other voltage levels. If needed, DSO have the possibility to request from the TSO, curtailment of generation or redispatch *of the largest units connected to their grid*. In Spain, DSOs can currently use DERs, *these large generators*, to solve congestions in the same way as the TSO does. This process, however, is done through the TSO in coordination with the DSO (i.e. by using an outdated process based on an email or similar sent by the DSO to the TSO). Once congestions in the distribution grid are identified and the DSO is not able to solve the grid problem during operation, the DSO can request a redispatch towards the TSO, given that there are generation units that have an impact on the congestion. The TSO then accesses the bids and calculates the necessary redispatch to solve the detected constraints. In case a resource is redispatched, it will be remunerated according to the existing market rules (which are the same as for the units re-dispatched due to congestions in the transmission grid). For planned curtailment, producers receive no financial compensation. In addition to congestion management, DSOs may also request a change to the TSO that is in the power factor range instructions sent to generation units with an installed capacity larger than 5 MW. Nowadays, this mechanism applies only to generators and not to demand.

Therefore, the DSO through the TSO can activate only the largest generators connected to the distribution grid for congestion management use distributed resources for local congestion management market and voltage control and consumers with contracted power above 5MW can participate in interruptible services. As both the DSO and TSO send these requests, ultimately the TSO receives the congestion management bids that can solve the constraints, selects the cleared bids and instructs the generators DER. Regarding the size of DER able to provide services for congestion management to the DSO there are no limitations with respect to the voltage level to which providers are connected. Participation is currently only allowed for the biggest generation units and pumped hydro units. As of today, in Spain, DSOs cannot sign interruptible contracts flexibility agreements with DERs. The only form of interruptible contract is between the TSO and industrial consumers. However, DSOs may use these interruptible contracts signed with the TSO to solve constraints in their networks as well. From February 2016, generation from renewable sources are also included in all the redispatching congestion management processes in the DSO or TSO is done via market mechanisms (Operation Procedure (PO) 3.2). However, since 2016 all congestion management situations have been solved through these market-based mechanisms.

Moreover, the Spanish demo also includes a local market platform to manage local congestions at the distribution grid level, where DER can offer flexibility. Once the DSO identifies potential congestion, the DSO sends a flexibility request to the local market platform and DER bids their flexibility. After the market clearance, DER are activated by the DSO. Then, the local market platform informs to the TSO of the DER activated as their activation might impact their Balancing Responsible Parties. It is important to note that the flexibility products in the local market are very different from the common (redispatching managed by the TSO) to have lower entrance costs and foster large participation from DER. In sum, the combination of both a common (resdispatching) and local market allows to better exploit most of the flexibility potentials from DER and have a large liquidity.

Coordinet project proposes alternative solutions for more active participation of resources, including DERs. In the congestion management markets, the processes that are currently performed manually can be performed in a semi-automated manner ensuring that the needed information is available to both the TSO and the affected DSOs. The purpose of this market would be to increase or decrease energy to solve grid congestions.

C. iFlex Project

Project basic information

Main goal: The iFLEX project aims to empower energy consumers by making it as easy as possible for them to participate in demand response programs, in which they adjust their energy consumption in response to signals or incentives coming from energy actors, such as price signals or bonuses. In addition, this project collaborates with the OneNet Project in the Northern cluster and provide an opportunity for small energy consumers to participate in the flexibility market. In this way, iFlex will deliver simultaneously implicit and explicit demand responses.

List of partners: VTT (Coordinator), Enerim, Caverion, Smart COM, JSI, Elektro Celje d.d., ECE d.o.o, ZPS, INTRACOM, HERON, OPTIMUS ENERGY, IN-JET.

Source of funding: European Union's Horizon 2020 research and innovation programme

Duration: 2020-2023

Webpage: https://www.iflex-project.eu/

Project learnings

Introduction

The goal of the iFLEX project is to make it easy and attractive for energy consumers to participate in demand response programs tailored to the needs of a renewable energy system. To achieve this, the project develops an intelligent assistant in collaboration with three European pilots and 600 consumers.

The iFLEX project creates a situation where prosumers benefit from lower electricity prices, smarter energy management and improved sustainability by being a flexible energy prosumer who offers to adjust consumption patterns according to the status of the energy system and its supply. The operation can be automated for convenience and also takes into account personal preferences ensuring comfort and stability.

This is the consumer experience that iFLEX is setting the scene for by introducing the iFLEX Assistant – an innovative software agent which supports consumers in managing when and how to be flexible by acting between them and their energy systems, various stakeholders and external systems, handling all the complexity of interactions. 'Using ground-breaking technology within Artificial Intelligence. The iFLEX Assistant creates a digital twin of the prosumers which learns and adapts to the consumption behaviour, control policies and system dynamics with the possibility of automating the decision-making. The latter is particularly desirable when you have an energy system of fluctuating renewables which calls for continuous and close to real-time demand response.

Architecture

The iFLEX project aims at empowering the consumers by making it as easy as possible for them to participate in Demand Response. A core concept of the project is the iFLEX Assistant, a novel software agent that acts between consumer(s), their energy systems, various stakeholders, and external systems helping them to achieve mutual benefits through local energy management and both explicit and implicit Demand Response (DR).

The focus is especially on households and DR for supporting the high penetration of renewables. The iFLEX Framework and iFLEX Assistant will be demonstrated and validated with real end-users in three different pilot clusters with specific focus areas and targeted end-users. The three iFLEX pilot clusters thus involve the active engagement of human subjects (participants) who will be provided with and testing the iFLEX system and solution, including the iFLEX Assistant.

In this regard, the iFLEX project design a common framework, which make an efficient interface between end users and building energy management system, energy metering systems, weather forecast, district heating and electricity energy provider, distribution system operators, electricity and flexibility market operators. Figure 19 shows the functional view of the common iFLEX Framework, while more details can be found in [RP1][68].

[68] D2.3 Initial Common architecture of iFLEX Framework, 2021, Online available: https://www.iflex-project.eu/?page_id=88

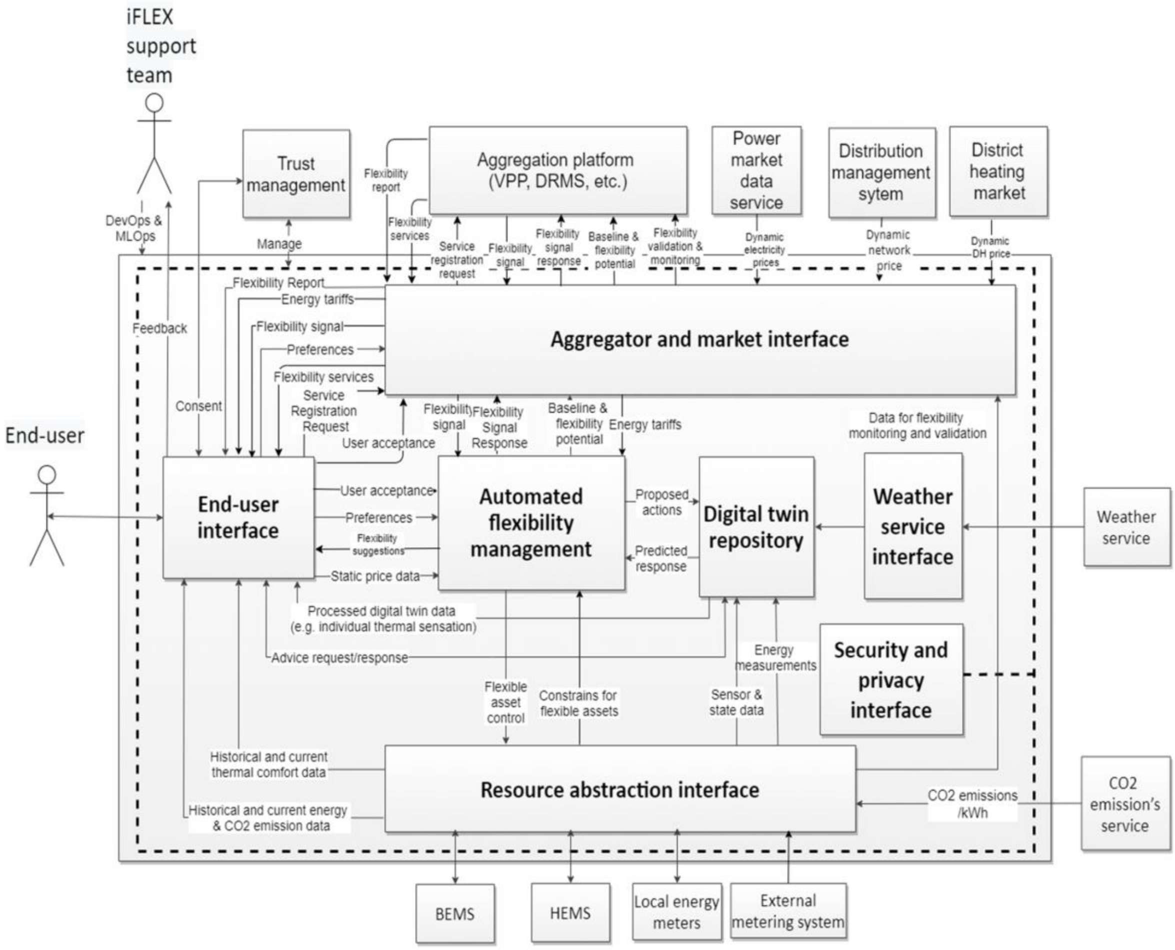


Figure 19: Functional view of the common iFLEX Framework

The iFLEX assistant models the energy consumption of a building using digital twin methodology and minimizes the energy cost of the building according to the end-user preferences, wetter forecast, and real-time and forecasted energy price (implicit demand response). In addition, the automated flexibility management block would offer the building flexibility to aggregator and market interface to optimize simultaneously the participation of end users in different explicit demand response programs.

D. OneNet Project

Project basic information

Main goal: The scope of the OneNet (One Network for Europe) is to create a fully replicable and scalable architecture that enables the whole European electrical system to operate as a single system in which a variety of markets allows the universal participation of stakeholders regardless of their physical location – at every level from small consumer to large producers.

List of partners: FhG, E-Redes, RWTH, UBE, VITO, ENG, ED, EMP, UoA, ELES, COMILLAS, EUI, EDSO, ENTSO-E, AST, Elektrilevi, ELEN, Elering, ESO, Fingrid, Litgrid, Nordpool, Piclo, ST, Vattenfall, Cybernetica, HEDNO/DEDDIE, IPTO/ADMIE, Protergia, EnergoInfo, UCY, CTSO, EAC, CINT, i-DE, UFD, RTE, ENEDIS, REN, INESC, IDEA, OMIE, NESTER, CEPS, EOP, PSE, ENSP, NCBJ, NKM, PSEI, BME, CEZ Distribuce, CEZ ESCO, EC, ECD, ECE, EG, EIMV, EL, FE/UL, GEN-I, MAVIR, MEI, Schneider, Unicorn, VUT, TTSA, EDE, EPRI, REScoop, EEIP, ENERC

Source of funding: EU's eighth Framework Programme Horizon 2020 titled "TSO – DSO Consumer: Large-scale demonstrations of innovative grid services through demand response, storage and small-scale (RES) generation" and responds to the call "Building a low-carbon, climate-resilient future (LC)"

Duration: 2020-2023

Webpage: https://onenet-project.eu/

Project learnings

Introduction

OneNet involves an unprecedented number of countries in a european project and aims at creating the conditions for a new generation of grid services able to fully exploit demand response, storage and distributed generation while creating fair, transparent and open conditions for the consumer. As result, while creating One Network for Europe, the project aims to build a customer centric approach to grid operation.

This ambitious view is achieved by proposing new markets, products and services and by creating a unique IT architecture to support innovative mechanisms of platform federation. The project also aims at creating wide consensus on the solution by launching a variety of initiatives including a large-scale forum for discussion within the international energy community. The complete concept is also proven in 4 cluster demos.

Objectives of the project.

The electrical grid is moving from being fully centralized to a highly decentralized system and grid operators have to change their operative business to accommodate for faster reactions and adaptive exploitation of flexibility. OneNet aims at performing this critical step by creating the conditions for a new generation of grid services able to fully exploit demand response, storage and distributed generation while creating fair, transparent and open conditions for the consumer. The scope of OneNet is to create a fully replicable and scalable architecture that enables the whole European electrical system to operate as a single system.

In this regard, the OneNet project will take seven steps, as follows:

- Define new and standardized products and services starting from project experience
- Identify appropriate market structures in support of the defined products and services
- Design open IT architecture supported by scalable data management enabling market structures
- Implement architecture in a reference version to be used as the basis for a European deployment
- Verify-in a set of large field tests the concepts and solutions proposed by OneNet
- Create European level consensus thanks to GRIFOn open forum with all the key stakeholders
- Push the result of OneNet in the standardization process for a significant market uptake

The OneNet project includes 4 cluster demos involving 15 European countries, as shown in Figure 20. The aim of these cluster demonstrators are as follows:

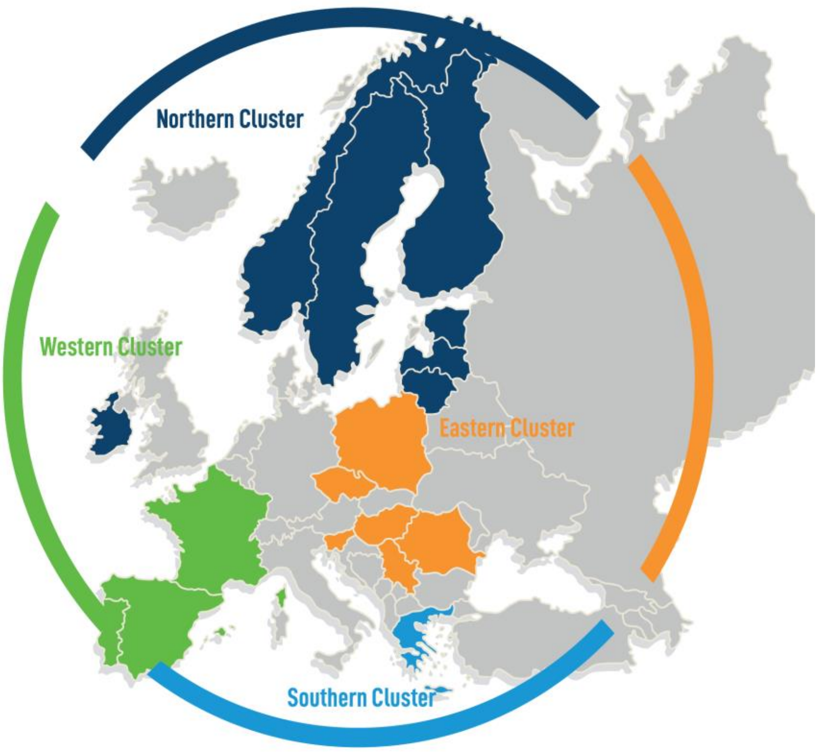


Figure 20: The demonstration pillars of the ONENET project

- *Northern Cluster (Ireland, Norway, Sweden, Finland, Estonia, Latvia, Lithuania)*: The Northern Demonstrator is an integrated effort by multiple TSOs and DSOs to enable market-driven flexibility uptake by these networks in a coordinated way through multiple markets where liquidity can be reached due to scope or existing trading volumes. Through this demonstration, the project will be able to show mapping and management of network needs in multiple use cases over multiple networks.

- Southern Cluster Demonstrator (Greece and Cyprus): The objective of the Southern Demonstrator is to prescribe, develop, implement and evaluate two pilot projects in Greece and Cyprus dealing with balancing and congestion management challenges facing system operators in the clean energy era, in compliance with the OneNet overall architecture. The results will be evaluated to provide recommendations for future market reforms in the region and harmonization for a panEU electricity market.

- *Western Cluster Demonstrator (Portugal, Spain and France)*: The Western Demonstrator will run in three different countries and will allow for the implementation of a wide range of flexibility mechanisms to address both DSO and TSO needs, including coordination between market mechanisms and the planning and real-time operation of the grids. Amongst the main goals to be achieved, increasing integration of renewables and anticipating operating scenarios are relevant priorities.

- *Eastern Cluster Demonstrator (Czech Republic, Poland, Hungary, Slovenia)*: The Eastern Demonstrator will develop an interoperable network of flexibility platforms to support the utilisation of various flexibility services, service integration and interaction, as well as the related data exchange. The development will be focused in particular on four areas: definition of new standardized flexibility services, elaboration of the related market-based product and grid prequalification processes, the conceptualisation of location-based service activation and the coordination of access to local and system-level services.

In these regards, the OneNet Cluster Demonstrators provide a platform of platforms to implement appropriate architecture for the integration of various platforms. For this purpose, the processes (use cases), architectures, and platforms of previous works, such as the INTERRFACE project, will be developed further in the OneNet project.

Early findings

Since the project started recently, the findings next stated are just from the initial analysis made in the few deliverables of the project that are already public (D2.1 and D2.2)69:

- A common feature among various projects is that regarding system services definition,they all consider addressing a scarcity/need by the network operator as the driver of the service. However, although they all consider different definitions of products, they all indicate that products are the means network operators use to solve the scarcities they face.

- The delivery of frequency control services, mainly provided by TSOs, includes a set of well established products that are considered in almost all projects evaluated, while for nonfrequency control services there appears to be more heterogeneity among the products definitions where all projects adopt their own product definitions.

- The majority of the projects address the coordination among main actors TSOs and DSOs and the arrangements or contracts of them with FSPs. However, a relevant share of reviewed projects concerns the joint coordination of TSO, DSO, and flexible service providers.

- From the national projects, OneNet can utilize mature concepts from flexibility marketplaces and platforms regarding assets prequalification process, data exchange architectures, developed interfaces among actors in the energy value chain, and innovative services directly provided by standardized products from existing wholesale markets

- The potential benefits of harmonising products could be reduced when these products are used to address needs that are specific to a location (e.g. needs to reduce congestion). The harmonisation of these products will still have positives effect as they would facilitate TSO-DSO coordination, DSO-DSO coordination as well as the investment decision-making by FSPs. As a result, harmonisation could still improve the efficiency of the system. An special case that needs to be consider is when products are harmonised not only across SOs but also across multiple services with some of those services not having a local component. In this case, the local component will only be relevant for some of the needs the product can address. As a result, when considering the potential for harmonisation, it is important to consider that, for the non-location related needs, harmonisation would facilitate the inter-regional trade while for the needs that have a location component, the harmonisation would benefit the coordination between different SOs.

- There are cases where products are developed to address very local problems. In those cases, harmonisation could reduce the value / capacity of the product to deliver the actual needs. Therefore, as reflected in regulation, harmonisation across these products could have negative effects.

- DSOs are still developing their understanding of the needs that are arising with the growing number of DER while TSOs have been addressing these challenges for a longer period of time. Harmonising the products used by the DSOs have the additional risk that the harmonised product could follow the requirements of the TSO (where more information is available) while it could (completely or partially) fail to deliver the needs of some of the DSOs. This risk would reduce over time as DSO develop a better understanding of its future needs and, as a result, further harmonisation could be feasible in the medium to long term.

- Not all barriers have the same effect on the potential for harmonisation. Barriers caused by intrinsic characteristics of the electricity systems (i.e. characteristics that cannot be changed or that can be changed at a very high costs) could constitute barriers to harmonisation in the long term. However, barriers based on non-intrinsic features of the energy system (e.g. legislation) should not have the same relevance in this analysis as they could be modified if harmonisation is shown to be beneficial.

[69] https://onenet-project.eu/public-deliverables/

- Boundary conditions should influence the set-up choices; however, market-based procurement through local flexibility markets involving the DSO, the TSO, or both, in an auction mechanism is of primary interest.

- Exists need for a standardised or, at least, harmonised vocabulary to be employed to discuss flexibility procurement. The need to have a clear understanding of the variety of procurement frameworks based on the consideration of harmonised concepts and use of a harmonised vocabulary calls for the adoption of analytical tools and shared market model frameworks.

E. FRESH Project

Project basic information

https://www.offis.de/offis/projekt/fresh.html

Project learnings

The electric vehicle represents new electricity demand and new ancillary services to the power grid. Unlocking the flexibility potential of the battery energy system enhances the renewable energy integration as well as the resilient operation of the power system. The home EV users have been long discussed for providing ancillary services, yet a fleet of battery-electricity transportation is emerging as a virtual power plant (VPP) for providing ancillary services in the energy market. The project FRESH aims at using this untapped flexibility from the fleet of automated guided vehicles (AGVs) in the Port of Hamburg to provide frequency containment reserve (FCR) without jeopardizing logistics. The vehicles can be temporarily removed from the logistic operation and connect with a charging station to provide electricity for other purposes. An aggregator can combine the fleet of electric vehicles and sell ancillary services via a tender platform operated by German TSOs. Nevertheless, it requires a 'pre-aggregator' for managing the small flexibility providers in the logistic process as shown in Figure 21.

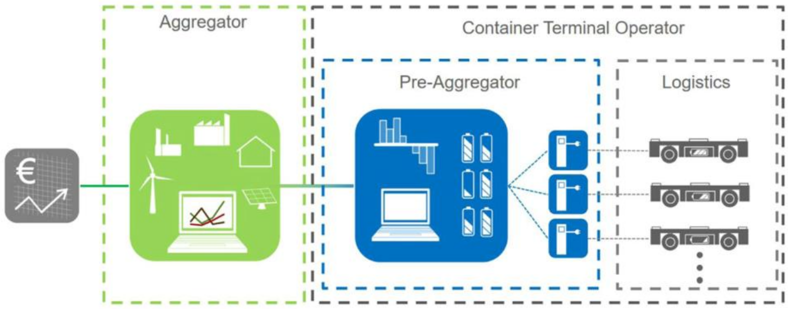


Figure 21 1 FCR provision in the logistics system[70]

For this purpose, a flexibility management system (FlexMan) has been developed in the FRESH project to forecast the day-ahead of the transport demand of the container terminal.

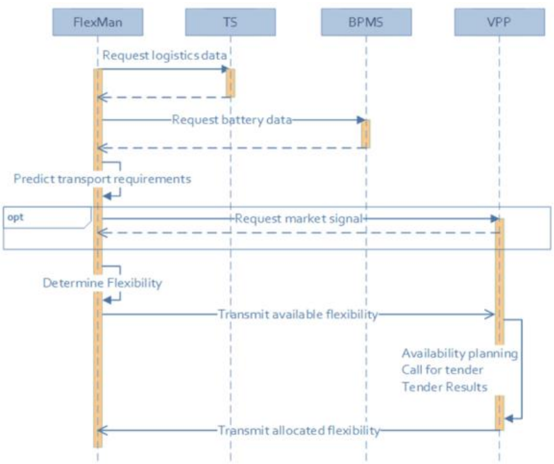


Figure 22 Sequence diagram of day-ahead planning phase[71]

The FlexMan uses artificial neural networks and multi-agent-based optimization to derive the FCR potential offer. However, it should be

[70] Reference: https://doi.org/10.1186/s42162-020-00129-1
[71] Reference: https://doi.org/10.1186/s42162-020-00129-1

noted that the FlexMan has no direct access to the energy market but behaves as the provision day-ahead planning before sending information to the aggregator. Figure 2 shows the process of the day-ahead planning for the FCR offer. Normally at the European energy market, the FCR auction takes place every day with four-hour symmetric products and delivers the next day. The day-ahead (D-1) planning can define the potential of the flexibility provided by the fleet as shown in Figure 22. The FlexMan forecasts the transport demand and optimizes the flexibility of the fleet by using relevant data such as logistics data, state of the charge, and market signals. The FlexMan transmits the available flexibility for the FCR tender. Once the tender result is known, the VPP allocates the flexibility within the pool and sends the data back to the FlexMan for the intraday operation. By using the FlexMan, the battery-electric fleet of AVGs can participate in the energy market for providing ancillary services to the system operators.

F. I-Automate Project

Project basic information

The increase of distributed energy resources (DERs) in the power system has driven the need for automated operation and control functions for better redispatching of the power plants to handle the variability and uncertainty of power supply and demand. Typical automated operation and control functions are centralized and located at the substation automation system (SAS) at the high voltage level. However, the DERs are connected at the medium and low voltage levels, which rises the demand for automated SASs significantly at the medium and lower voltage network. Additionally, the protection and control functions are specially designed and implemented on hardware. This requires a large number of sensors and actuators; however, time-consumption and high investment costs may discourage the distribution system operators (DSOs) to implement them. In addition, the installation and configuration process must be done by the person on the job, which is bundled with proprietary manufacturer software and protocols making the whole life cycle with operation and maintenance inflexible. In order to tackle these challenges, the i-Automate project proposes a modular, configurable, and testable automation architecture for smart grids as shown in Figure 23.

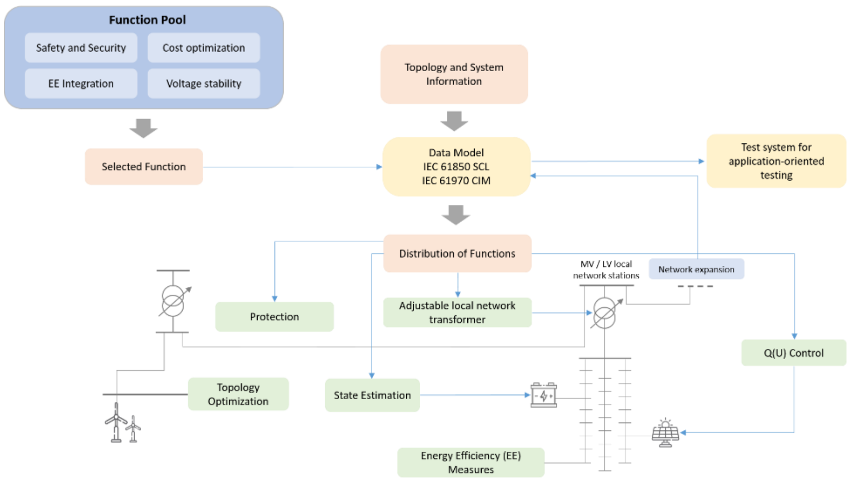


Figure 23 Modular automation architecture for configuration and testing

A function pool provides a wide range of implementations of smart grid functions, e.g. energy efficiency integration, Q(U) control, and network security, in which hardware and software are decoupled from each other. The modular configuration uses the following data models: IEC 61850-6 (Substation Configuration Language, SCL) or IEC 61970-301 (Common Information Model, CIM). The information contained in the data models is used for the configuration linked to a specific module in the function pool. For this purpose, topology information must be automatically transferred to a suitable software (middleware), where distributed data storage and data management are located. In addition, the information contained in the data models can also be used to perform test scenarios that are essential, especially for new system solutions. In addition to the predominantly local protection functions known today, the supercoordinate smart grid automation functions can also be taken into account for the communication between TSOs and DSOs. This concept was implemented in the pilot project at a distribution network in Germany.

The modular and flexible architecture approach can reduce capital expenditure (CAPEX) and operating expense (OPEX) for all parties. In this way, the smart grid technology can reach the maximum of its capacity to provide flexibility and resiliency by enabling ancillary services of the small, distributed prosumers to the system operator.

G. Enera Project

Webpage: https://www.offis.de/en/offis/blog/article/enera-an-important-step-for-the-energy-transition.html

Project learnings. Battery energy storage systems provide a wide range of flexible services to system operators as well as increasing self-consumption to a prosumer. Managing the flexibility aggregation of distributed energy storage providers is a technical challenge due to the lack of efficient market mechanisms and regulations. The study on the agent system for battery energy storage has been the research interest for a decade but yet paves the way into practice on how to vividly communicate the potential distributed battery energy storage system. In addition, the proactive consumer can also provide flexibility such as heat pump operation. The ENERA project is one of five projects within the "Smart Energy Showcase – Digital Agenda for the Energy Transition" (SINTEG) research program, which aims at developing solutions for a climate-friendly, efficient, and secure energy supply with a high percentage of renewable energy and to demonstrate these solutions on a large scale. A citizen storage system (Bürgerspeicher) is one of the potential business models for supporting the innovative flexibility options to the energy system. A simulation model is used to optimize the self-consumption of a neighbourhood citizen storage system consisting of proactive consumers and flexible prosumers with one or more battery systems. The simulation model is based on the co-simulation platform mosaic[72], allowing the design of several scenarios according to determine the individual configuration for each citizen storage requirements. In this way, the created scenario can optimize the self-consumption in conjunction with the associated costs, which can be performed through the Geo-Dashboard, Fig.1. The user can adjust the component and its characteristics for a specific scenario such as an annual consumption, number of occupants, household size, and duration of the scenario. The generated data from the simulation can be visualized in the web application as well as the comparison between scenarios.

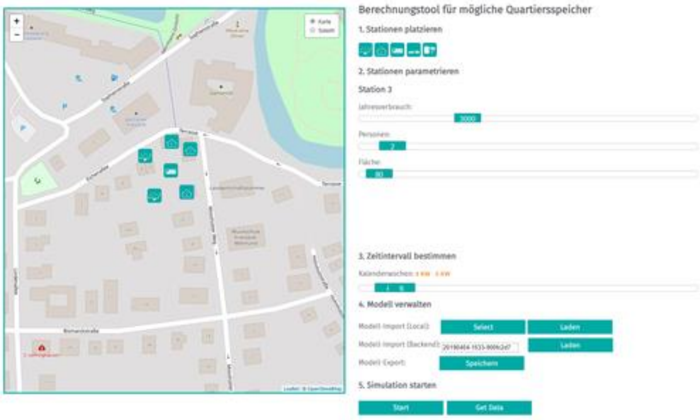


Figure 24 Web-based Geo-Dashboard of citizen storage (Bürgerspeicher)[73]

The citizen storage platform can help to tackle the uncertainties before the investment by simulating the scenario and comparing with other options. For example, the user can foresee the uncertainty of electricity generation from PV be stored in the battery system or feed-in to the electricity network with/without additional investment. This software solution allows the user to examine different scenarios to determine the profitable investment strategy.

H. ANM4L Project

Project basic information

Main goal: The ANM4L project aims at demonstrating how innovative active network management (ANM) solutions can increase the integration of renewable energy sources in electricity distribution networks. Alternatives to traditional network expansion are needed to ensure sustainable development of the power grids. New technologies, methods, and markets are emerging to provide increased flexibility in consumption, generation, and power transfer capacity. The ANM4L project will develop solutions to enable integration of renewables with the agility required from developments in demand and production.

List of partners: RISE(Coordinator), Lund University, RWTH Aachen, Lumenaza, E.ON, Municipality of Borgholm

Source of funding: ERA-Net Smart Energy Systems initiative Integrated, Regional Energy Systems

Duration: 2019-2022

Webpage: https://www.anm4l.eu/

Project learnings

Introduction

Active Network Management (ANM) is the exploitation of flexible network assets for the purpose of providing secure means of increasing grid utilisation. ANM solutions involve advanced control systems often relying on increased monitoring of key network quantities in the grid and enhanced communication between the flexible network assets, the grid operators, as well as other stakeholders. Flexible network assets are resources in the power system with the ability of being controlled to support grid needs.

[72] (cf. http://mosaik.offis.de/)
[73] Reference: https://projekt-enera.de/wp-content/uploads/enera-projektmagazin.pdf

Alternative Grid Development solutions such as ANM has an impact on the resilience level built into the grid, where traditional solutions (such as building more grid infrastructure) based on conventional solutions have well known behaviour and reliability levels. ANM on the other hand is relying on other systems (including integrated monitoring, control, and communication infrastructure) with a behaviour directly depending on the flexible network assets. This means that the developed ANM solutions must be rigid and reliable in order not to have negative impact on the over-all resilience.

Alternative Grid Developments imply an impact for both how the grid is being planned and operated. In the long-term investment planning, future scenarios are the basis where different grid development solutions are weighted against each other based on e.g., their resilience, cost, environmental impact, and time to operation. In the shorter-term maintenance planning, equipment outages are planned ahead based on historians and forecasts together with actions to limit the impact on the customer. For operational planning, short term forecasts influence the need to take preventive actions, while during operation events occurring may result in additional mitigating actions to be taken to maintain the electricity supply.

The solutions developed in the ANM4L project are based on three pillars:

- **ANM control solutions**: development of solutions to utilise and control flexible network assets to meet the basic electro-technical grid requirements in maintaining voltages and currents within acceptable limits
- **Business solutions**: development of the cost-benefit-analysis of implementation and utilisation of ANM solutions, as well as business cases for owners of flexible network assets
- **ICT solutions**: development of dedicated solutions for interfacing monitoring and control of flexible network assets and the different users, as well as integrating with IT solutions and infrastructure, based on open-source solutions with high level of interoperability
- These three pillars are collectively resulting in a toolbox developed to support the operation and planning of distribution grids, which functionality and replicability will be tested and demonstrated within the ANM4L project.
- **Grid limitations and control activation of flexible network assets,**[74] [75]
- Grid capacity may be limited by equipment rating as well as voltage fluctuations. While voltage levels are local and can be handled locally, congestion leading to risk of overload are aggregated issues which require communication and coordination. Additional limitations for distribution grids include regulations of the interface towards the transmission grid, which may consider both the reactive power exchange as well as the maximum active power demand. Active Network Management control to prevent any of these limitations being breached, may comprise both local and centralised control solutions regulating the active and/or reactive power of flexible network assets according to their individual capabilities. The effectiveness of controlling either active or reactive power differs depending on the network configuration.

The ANM4L project distinguish three main type of flexible network assets: load, generation, and equipment in the grid (e.g., shunt banks and tap-changers). The assets have different possibilities of being controlled and do also have different levels of costs related to such control. As an example, loads can typically only be controlled based on active power, while generation may be able to control active and reactive power independently.

The financial models to enable the DSO to activate flexible network assets are in the ANM4L project distinguished as two types: long-term contracts or short-term trading.

- For long-term contracts, a contractual bi-lateral agreement is made between DSO and customer allowing the DSO to instantly access and activate a flexibility resource upon demand. In the ANM4L project, this is defined as Demand Side Management (DSM).
- In case of short-term trading, flexibility requests and offers are matched on a market enabling the DSO to procure flexibility upon demand for a specific hour. In the ANM4L project, this is defined as Demand Response (DR).

Both DSM & DR can be considered market-based approaches, with the major difference being that a DSM solution allows the DSO to have an asset pool to which it has direct control at any given time while resources based on a DR solution are only available after a case-by-case trade agreement is in place.

A centralised ANM control solution can utilise a flexibility dispatch list to order the available flexible network assets by monetary costs and/or technical efficiency, before taking the decision on activating the flexibility. In this way, the flexibility dispatch list enables an optimal utilisation of flexibility for a given scenario with a given number of available flexible network assets.

The ANM4L toolbox. The toolbox is divided into two main functional parts, one for operation and one for planning.

Planning: The planning part involves a scenario-based simulation module, where control algorithms and flexible network assets are providing the technical ANM solutions which would be meeting the scenario requirements. The identified solutions are then assessed financially through a CBA module, which adds the financial aspects to the ANM solutions. Interfaces of the modules and to the user enables the toolbox to provide the basis of the ANM solutions as decision support to the network planner.

Operation: The operation part includes direct control of flexible network assets, based on monitoring of voltages and currents and the control algorithms. Interfaces include monitoring equipment, flexible network assets, the owner of flexible network assets to enable a market-based interaction, as well presentation of information and decision support to the network operator.

[74] M. Edvall & S. Nyström, "*Characterisation of flexibility resources*", Deliverable D4.2 ANM4L, 2021
[75] O. Samuelsson & M. Lundberg, "*Report on ANM control algorithms for active & reactive power*", Deliverable D3.1 ANM4L, 2021

The functionality of the toolbox with the planning and operational parts will be tested through demonstrations in distribution grids in Sweden and Hungary. In Sweden, the integration of wind power is today resulting in congestions and the demonstration of the operation part will therefore include the impact of a wind power plant. In Hungary, it is foreseen that increases in PV penetration will become a constraint and the demonstration will therefore involve the assessment of a present PV plant. The planning part will be tested on various future grid development scenarios in Sweden, and the replicability of the functionality will be assessed for Hungary.[76]

I. FARCROSS Project

Project basic information

Main goal: FARCROSS (FAcilitating Regional CROSS-border Electricity Transmission through Innovation) aims to connect major stakeholders of the energy value chain around Europe and demonstrate integrated hardware and software solutions that will facilitate "unlocking" of the resources for the cross-border electricity flows and regional cooperation.

The project propose state-of-the-art digital technologies into the power system, in order to enhance and optimize the coordinated effort between TSOs and between TSOs–energy producers, and establish a next generation electricity market which will operate on a regional basis and will benefit from disperse assets and increased presence of RES, thus creating in comparable economic benefits to the stakeholders of the chain.

List of partners: The project has 31 partners from 16 European countries representing transmission and distribution system operators, service providers, research institutions and universities, and manufacturers

Figure 25: FARCROSS partners

[76] E. Hillberg, et.al., "*Active Network Management for All – ANM4L – a collaborative research project*", White paper ANM4L, 2020

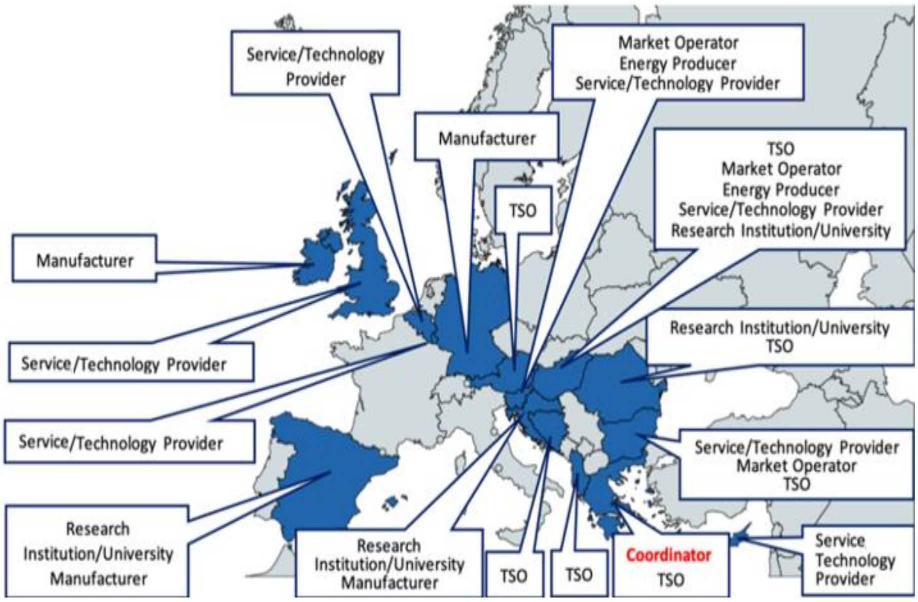


Figure 26: FARCROSS partners profile

Source of funding: European Union's Horizon 2020 research and innovation programme (LC-SC3-ES-2-2019 call)

Duration: 2019-2023

Webpage: https://farcross.eu/

Project learnings

Project objectives:

- Develop and introduce advanced software solutions that will increase cross-border capacity and the potential of cross-border grid services;
- Design and propose a robust set of technical and market codes enabling the building up of the harmonization of the network codes, and potentially integration to the national electricity markets;
- Design and present a cost-benefit analysis (CBA), based on the outcomes and lessons learnt from the project implementations and demonstrations, to enhance the planning of cross-border infrastructure investments;
- Demonstrate hardware and software technologies and relevant concepts in realistic environments; the FARCROSS project engages TSOs and energy producers in 8 countries;
- Facilitate further research and new market opportunities across the energy industry by ensuring an efficient dissemination of the FARCROSS outcomes to key stakeholders.

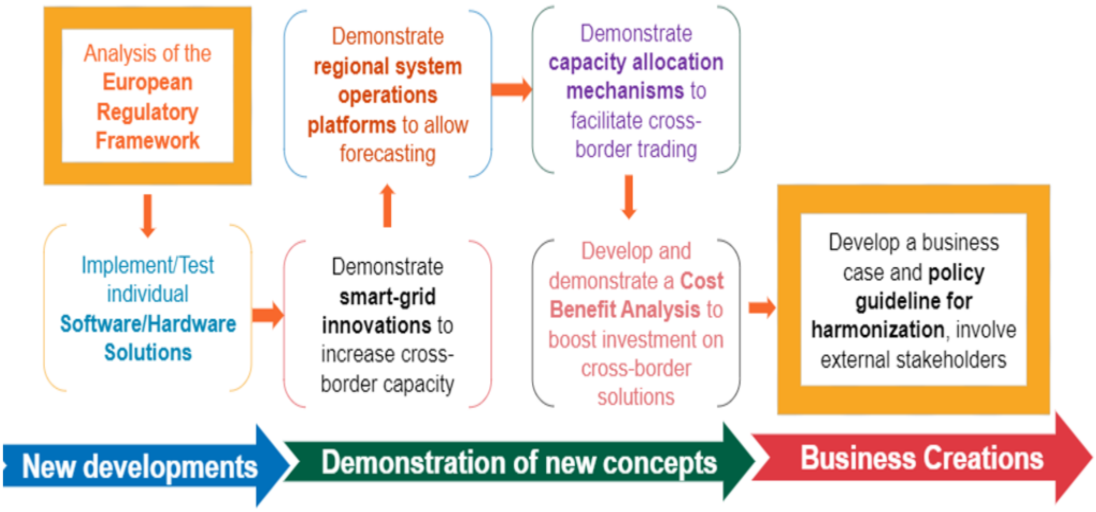


Figure 27: FARCROSS methodology

FARCROSS demonstrators

5 demos in 8 different countries will apply hardware and software tools to provide cross-border engagement, better harmonization, flexibility solutions, forecasting services and further RES penetration:

- Unlocking Cross-Border Capacity with Modular Power Flow Control Solutions (MPFC DEMO)
- Complex grid management technology for handling cross-border transmission line capacity-related issues (DLR-H DEMO)
- Implementation of a Wide-Area Protection, Automation and Control system (WAMPAC) applied to Cross-Border Transmission Systems (WAMS DEMO)
- Pan-European Deep Modelling Framework for improved system operation planning/forecasting and analysis on the inter-TSO level (EUROPAN DEMO)
- Co-optimized cross-border capacity auction algorithm (OPTIM-CAP DEMO)

The demonstration trials will be executed in 3 demo areas, in the aim to address:

Demo area A: Smart Grid Innovations to increase cross-border capacity, by involving TSOs' grid infrastructures, and deployed in specially designed regional use-cases (scenarios) to improve the grid flexibility and enhance significantly the cross-border flows.

Demo area B: Regional System Operations platforms development, to allow improved system operation forecasting on the TSO level, which will contribute to the transmission grid security and quality of supply. Pilots will run in the SEE and SCC countries ensuring the best possible flow of information among the TSO participants and the achievement of optimal system operation at the minimum cost through the maximum possible usage of the existing infrastructure.

Demo area C: Capacity allocation for regional cross-border trading, by optimizing the usage of the available transfer capacities for reserve procurement and for energy trading, building on top of the current ATC based simple transfer capacity auction algorithms, thus assuring the system security and the more effective and valuable allocation of the grid capacity.

Figure 28: FARCROSS demo countries

Summary of achievements during the first 18 months

During the first 18 months of the project, activities related to the design, preparation and installation of the demos took place, as well as horizontal activities about ethics requirements, project and technical management, quality assurance, data and innovation management, stakeholder involvement and clustering, exploitation and impact-value creation as well as communication, dissemination and awareness-raising. In addition, regulatory and legal challenges to innovation were addressed. The CBA framework methodology for smart grid and market innovations in the pan-EU context has been introduced as well as a methodology for development of project-level KPIs.

The main results achieved so far are the timely submission of the planned deliverables and the achievement of the associated milestones. Concerning the demos' progress, initial studies were conducted to identify suitable MPFC solutions and the MPFC deployment design was completed. The 8 demonstration transmission lines were selected for the DLR-H demo and the sensors were pre-tested and installed.

Furthermore, the oscillation detection algorithms were identified, the WAMPAC solution was tested in the laboratory, the WAMPAC architecture and the PMU locations were finalized. The definition of the EUROPAN architecture and system requirements, the system infrastructure developments and the first version of the energy analysis module and the EUROPAN frontend have been completed. Last but not least, the market design and the IT architecture for the cross-border co-optimized energy-reserve allocation were defined.

More specifically:

- An analysis of the regulatory framework and RES integration of the countries participating in the demos describing challenges, status and innovation tools, identifying similarities and differences on how their electrical grid operates in order to find out the potential of cross-border harmonization between these countries has been concluded.
- The MPFC deployment design was completed maximizing the impact of power flow control devices on cross-border lines.
- A complex expert system has been designed and implemented, which serves as both a complex transmission grid management system and a health monitoring system.
- The DLR-H system design enables the TSOs to closely monitor the condition of the transmission line and take advantage of every moment its maximum transfer capacity of power, given the weather ambient conditions. As the project currently stands, all demonstration sites have begun the data collection phase.
- The design and implementation of the WAMPAC system introduced an automatic toolbox that includes scenarios, modal analysis, dynamic events, results and detection algorithms.
- The EUROPAN's novel technical approach for high resolution weather forecasting enables energy quantities derived on a unit level and then aggregated towards higher 'abstraction layers'. The selection of appropriate models is made for each quantity and a computational acceleration is achieved via Neural Networks, providing added value for grid observability and alarms. This new approach helps accomplish the tasks of facilitating the increase of RES, ensuring the system security and operational capacity to address the internal electricity market needs.
- The OPTIM-CAP demo introduced a novel market design, featuring co-optimized day-ahead auction covering both energy and balancing capacity procurement in coupled bidding zones.
- An innovative CBA methodology approach has also been adopted and project specific KPIs have been introduced.

Progress beyond the state of the art and expected results until the end of the project

Significant progress beyond the state of the art has been achieved during the first reporting period. An analysis of the regulatory framework and RES integration of the countries participating in the demos describing challenges, status and innovation tools, identifying similarities and differences on how their electrical grid operates in order to find out the potential of cross-border harmonization between these countries has been concluded. The MPFC deployment design was completed maximizing the impact of power flow control devices on cross-border lines. A complex expert system has been designed and implemented, which serves as both a complex transmission grid management system and a health monitoring system. The DLR-H system design enables the TSOs to closely monitor the condition of the transmission line and take advantage of every moment its maximum transfer capacity of power, given the weather ambient conditions. The design and implementation of the WAMPAC system introduced an automatic toolbox that includes scenarios, modal analysis, dynamic events, results and detection algorithms. The EUROPAN's novel technical approach for high resolution weather forecasting enables energy quantities derived on a unit level and then aggregated towards higher 'abstraction layers'. The selection of appropriate models is made for each quantity and a computational acceleration is achieved via Neural Networks, providing added value for grid observability and alarms. This new approach helps accomplish the tasks of facilitating the increase of RES, ensuring the system security and operational capacity to address the internal electricity market needs. The OPTIM-CAP demo introduced a novel market design, featuring co-optimized day-ahead auction covering both energy and balancing capacity procurement in coupled bidding zones. An innovative CBA methodology appoach has also been adopted and project specific KPIs have been introduced.

The expected results until the end of the project can be summarized as follows:

- Introduce an executable framework for implementing pathways for improved cross-border harmonization.
- Finalize the system development and the deployment works.
- Perform the forecasting and grid services analysis.
- Finalize the new mathematical model for the optimization algorithm and an updated, scalable and high-performance algorithm prototype.
- Run and evaluate the results of the demos, perform the CBA and the impact assessment.
- Develop a scalability and applicability plan at EU level and provide recommendations for rolling-out of innovations and services.
- Report on clustering activities and the stakeholders' involvement.

FARCROSS impact

The main potential impacts are the enhancement of regional cooperation in transmission grid operation by driving common approaches to grid services that increase cross-border flows and flexibility and by improving cross-border wholesale market operation, the improvement of flexibility by optimizing the use of large-scale assets and infrastructure investments and the improvement of system security in the context of increasing levels of renewable energy. The project has achieved socio-economic impact and wider societal implications during the first reporting period. FARCROSS has participated in communication, clustering and awareness raising activities promoting the project and its results with digital and physical means. FARCROSS focused on market coupling, improved cross-border energy flows, better resource forecasting, and better utilization of capacity margins and is developing state-of-the art digital technologies, innovative h/w, systems and processes. In addition, it enabled coordinated efforts between cities, regions and member states as it is building strong market, technology and electricity system links that are based on generation, demand and RES characteristics.

Summarizing, the FARCROSS project ambition is to:

- Successfully integrate large amounts of renewable generation. These resources are intermittent and there are advantages to geographic dispersion. FARCROSS proposed solutions can be used to increase cross-border flows allowing other countries from importing clean energy and to maximize EU-wide renewable generation;
- Reduce the need to build new infrastructure by first optimizing the existing network, whereas at the same time to achieve reduced environmental impact compared to alternative options and minimize total costs to customers;
- Shorten connection lead-times, as FARCROSS solutions can be installed in relatively short timeframes, can minimize the grid modifications needed to integrate new sources of generation or serve as a bridge solution.

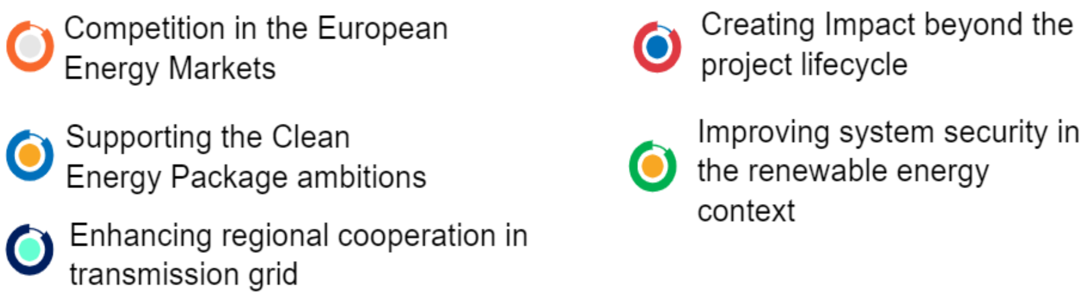


Figure 29: FARCROSS impact

J. Interrface Project

Project basic information

Main goal: INTERRFACE strategic objectives are:

- To create a common architecture that connects market platforms to establish a seamless pan-European electricity exchange linking wholesale and retail markets and allows all electricity market players to trade and procure energy services in a transparent, non-discriminatory way.
- To define and demonstrate standardised products, key parameters, and the activation and settlement process for energy services.
- To drive collaboration in the procurement of grid services by TSOs and DSOs, and to create strong incentives to connected customers, by improving market signals and allowing them to procure services based on specific locations and grid conditions.
- To integrate small scale and large scale assets to increase market liquidity for grid services and facilitate scaling up of new services which are compatible across Europe.
- To promote state-of-the-art digital technologies that consumers are familiar with in other everyday transactions (i.e. e-auctions, e-commerce, e-banking, social networks), into the electricity value chain, in order to engage end-users into next generation electricity market transactions, creating incomparable economic benefits by deferring conventional energy infrastructure investments.

List of partners: The project has 42 partners from 16 different European countries, representing transmission and distribution system operators, service providers, research institutions and universities, aggregators, and a power exchange:

Figure 30 Interrface Project Partners

Source of funding: European Union's Horizon 2020 research and innovation programme

Duration: 2019-2022

Webpage: www.interrface.eu

Project learnings

The European Energy System has been undergoing a radical transformation during the latest decades. Technology and innovation disrupt the traditional models from generation to beyond the meter; and this has been amplified and reinforced by the electrification of large sectors of economy, decentralisation of power-generating assets, digitalization of the grid. Energy efficiency has been placed on the top rank, together with EU's global leadership in RES and the need for consumers to be active and central players of the energy market of the future. This clean energy transition in the growth sector of the future, has caused a transformation of the European electricity system; novel technologies are now available and reinforce the electrification of large sectors of economy, the decentralisation of power generation resources but also the digitalization of the grid. These three trends act in a virtuous circle and their combination amplifies their impact on carbon reduction, customers engagement and real-time interaction with the system. In this way, traditional boundaries between actors are blurred, new actors become part of the value chain, thus increasing the complexity of the system governance.

It is a necessity nowadays for DSOs to cooperate with TSOs in planning and operating their networks and exchange all necessary information and data regarding the performance of generation assets and demand side response, the daily operation of their networks and the long-term planning of network investments, so as to ensure the cost-efficient development and secure and reliable operation of their networks.
Moreover, TSOs and DSOs shall cooperate to achieve coordinated access to resources such as distributed generation, energy storage, etc. to support the needs of both distribution and transmission systems; in the meantime, European Commission urges Member States to provide the necessary regulatory framework and incentivise DSOs to procure services in order to improve efficiencies in the operation and development of the distribution system.

Technical and Operational Objectives are:

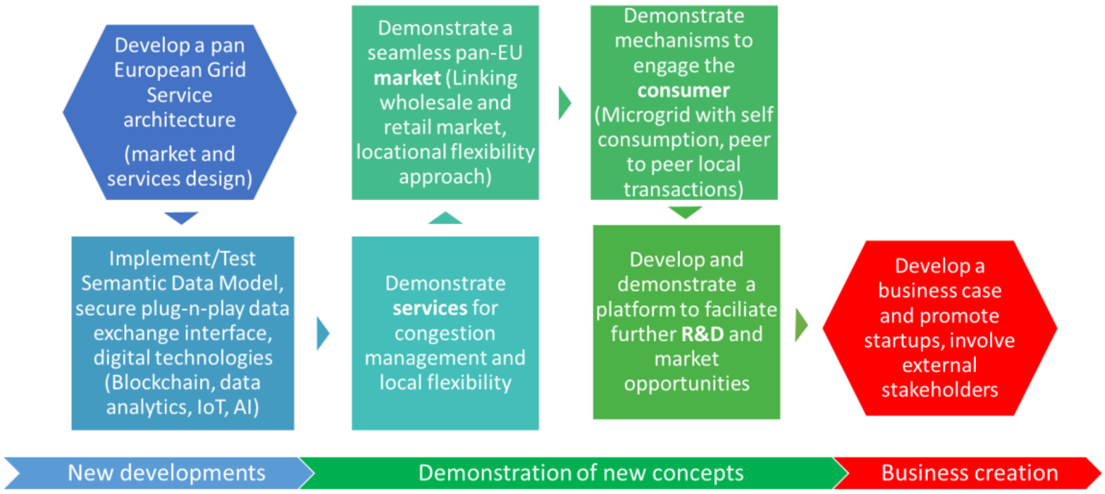


Figure 31 Interrface Technical and Operational objectives

1. To design an Interoperable pan-European Grid Services Architecture (IEGSA) that will connect market platforms in a transparent, non-discriminatory manner and will allow a pan-European electricity exchange that will link wholesale and retail markets and will enable the trading of energy services.
2. To design, develop and deploy a reference IT infrastructure - to materialise IEGSA architecture and facilitate the operation of the aforementioned services and the adaptation of energy market tools.
3. To test the state-of-the-art digital technologies, such as Blockchains and IoT, for peer to peer energy transactions that promote local markets and smart asset management.
4. To mitigate congestions and activate local flexibility resources for system balancing services through innovative platforms, operated by TSOs and DSOs in a coordinated manner.
5. To promote the integration of DERs into the electricity markets, demonstrating mechanisms and platforms leading to the establishment of a seamless pan-European market empowering all market participants to provide energy services in a transparent and non-discriminatory way.
6. To engage consumers into electricity markets with clean energy flows based on a user- operator "alliance" that offsets the variability of renewable energy with effective demand response, active control, distributed storage and peer-to-peer local markets.
7. To demonstrate the IEGSA components and architecture and the relevant IT infrastructure.
8. To facilitate further research and new market opportunities across the energy industry by ensuring an efficient dissemination of the INTERRFACE outcomes to key stakeholders.
9. To create the foundation of new business opportunities, with the selection of SMEs and startups that will be selected through an Open Call -following a cascade funding mechanism- for the development of new services.

Interoperable pan-European Grid Services Architecture (IEGSA). To support the European energy transformation, the INTERRFACE project designs, develops and exploit the Interoperable pan-European Grid Services Architecture (IEGSA) to act as the interface between the power

system (TSO and DSO) and the customers and allow the seamless and coordinated operation of all stakeholders to use and procure common services. In the frame of this development, state-of-the-art digital tools will provide new opportunities for electricity market participation and thus engage consumers into the INTERRFACE proposed market structures that will be designed to exploit Distributed Energy Resources.
The aim of the IEGSA is to act as a common architecture that connects market platforms to establish a seamless pan-European electricity exchange linking wholesale and retail markets and allows all electricity market players to trade and procure energy services in a transparent, non-discriminatory way.

The IEGSA aims to drive collaboration in the procurement of grid services by TSOs and DSOs, and to create strong incentives to connected customers, by improving market signals and allowing them to procure services based on specific locations and grid conditions. The architecture allows for integrating small scale and large scale assets to increase market liquidity for grid services and facilitate scaling up of new services which are compatible across Europe. The development of the IEGSA is not restricted only to the IT architecture, but the process also includes the definition and demonstration of standardised products, key parameters, and the activation and settlement process for energy services. Through these functions the IEGSA is able to mitigate congestions of the grid at the various voltage levels and to activate local flexibility resources for system balancing services through innovative platforms, operated by TSOs and DSOs in a coordinated manner. In addition to this, the architecture engages consumers into the electricity markets with clean energy flows based on a user-operator "alliance" that offsets the variability of renewable energy with effective demand response, active control, distributed storage and peer-to-peer local markets.

IEGSA platform has been deployed in 9 different countries, following the demonstrators of the INTERRFACE project, namely in Estonia, Latvia, Finland, Greece, Italy, Bulgaria, Romania, Slovenia and Hungary. Local TSOs and/or DSOs have been involved in each country as members of the consortium to safeguard the compliance of the solutions to the diverse national policies and regulations, while at the same time covering the requirements of the demonstrators and following a more generic/centralised approach, pertaining to standards and by defining harmonized product and services definitions. The demonstrators cover three pillars or thematic areas, namely: congestion management and balancing, peer-to-peer trading and pan-EU electricity market.

Although the particularities of each region were taken into account, the INTERRFACE consortium put an effort in developing standardized definitions for the ancillary service and balancing markets that could be applicable across Europe, thus leading to a more coordinated and efficient market operation and market coupling among countries. We focused on services such as aFRR, mFRR, short-term congestion management and operational congestion management.
TSO-DSO coordination was also targeted by the project by the definition of coordination schemes. Towards this goal, the Active System Management Report of ENTSO-E and the European DSO associations was used as a basis. Following this we ended up with several coordination schemes:

- Market options in which TSO and DSO congestion management is separated. Differences of market options with respect to the merit order list management are examined (separated, partially overlapping, or fully integrated).
- Market options in which TSO and DSO congestion management is combined and managed by the same market.
- Market options in which TSO and DSO congestion management can access to balancing resources too

Finally, the IEGSA platform taking advantage of its powerful data management middleware supports all processes that surround the market operation, spanning from Portfolio Management for Aggregators to Product, Grid and Bid Qualification, Services and Product definitions, Services Procurement, Activation of Services and finally the Energy Settlement.

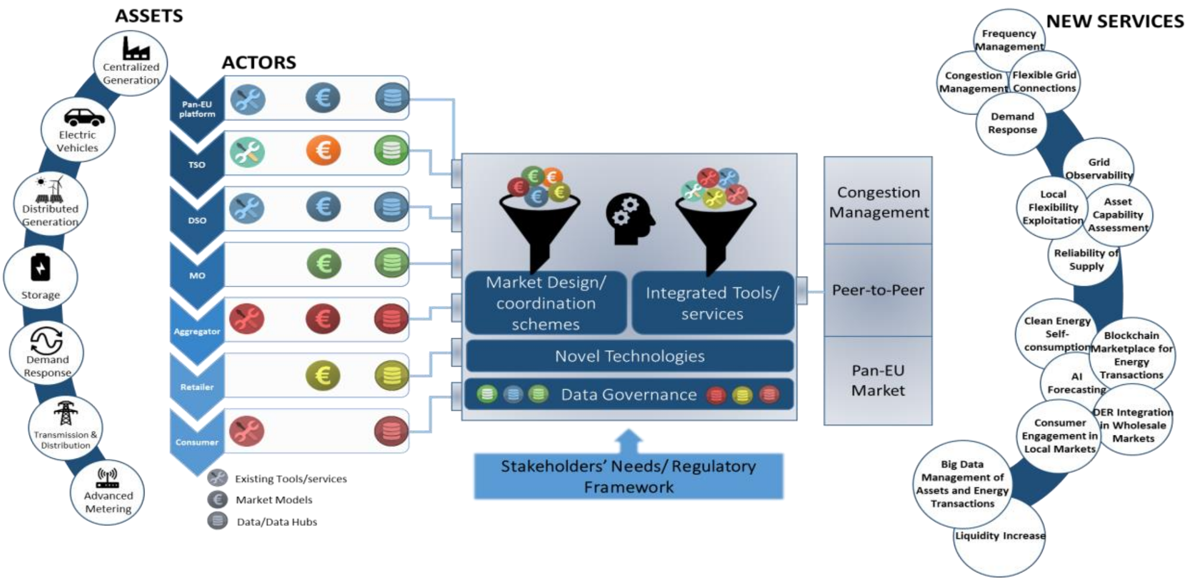


Figure 32 Technical Framework - IEGSA Platform

K. OSMOSE Project

<u>Project basic information</u>

Main goal: The OSMOSE project aims to identify and develop the optimal mix of flexibilities for the European power system to enable the Energy Transition. Four large-scale demonstrators led by Transmission System Operators explore the technical and economic feasibility of innovative flexibility services and providers, including: grid forming, multi-services by hybrid storage, near real-time cross border exchanges, and smart zonal energy management system.

List of partners: RTE (Coordinator), REE, TERNA, REN, ELES, ELIA, EDISON SPA, HSE, SAFT, GREENPOWER, ABB, IBM ITALIA, EFACEC ENERGIA, ENEL, CEA, EPFL, DAUPHINE, UDE, TUB, RSE SPA, ENSIEL, ULPGC, CENER, IT4POWER GMBH, EKC, R&D NESTER, ENG, E2I, INGETEAM, HDE SRL, SCHNEIDER, FBK.

Source of funding: European Union's Horizon 2020 research and innovation programme under grant agreement Nº 773406.

Duration: 2018-2022

Webpage: https://www.osmose-h2020.eu/

<u>Project learnings</u>

The European power system is facing new challenges, and in particular the increasing penetration of Renewable Energy Sources. But in parallel, new solutions are also emerging such as smarter controls or large-scale storage.

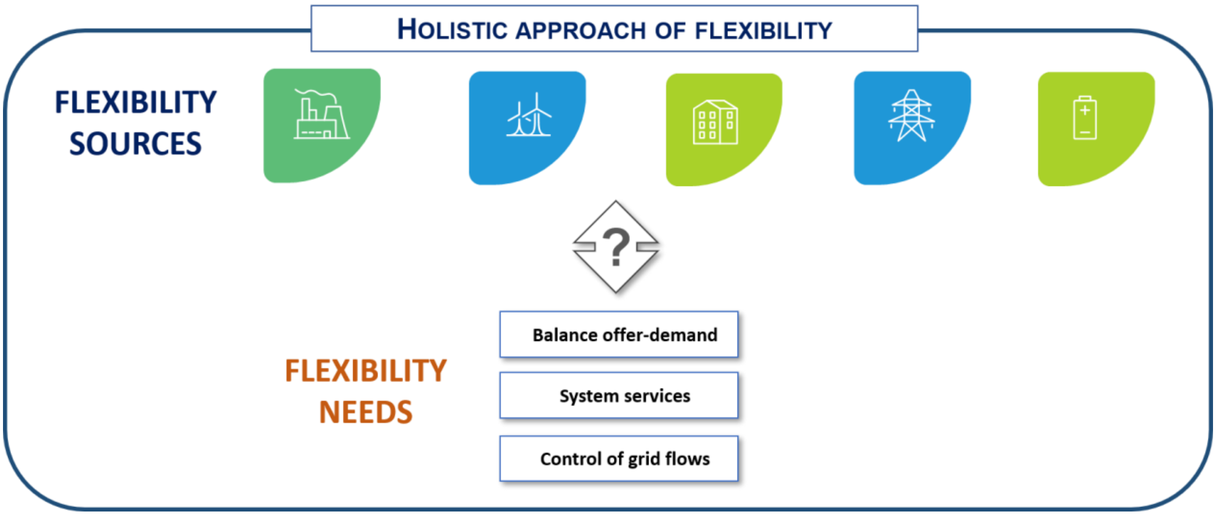


Figure 33 OSMOSE Project Approach

OSMOSE develops an approach to capture the synergies across different needs and sources of flexibilities.

Osmose approach to flexibility. Flexibility is understood as a power system's ability to cope with variability and uncertainty in demand, generation and grid, over different timescales. The project aims for the development of flexibilities that can be used for a better integration of renewable energies. A holistic approach is adopted, considering at the same time:

- the increased need of flexibilities in the system (mainly improved balance of supply and demand in electricity markets, provision of existing and future system services and allowance of a dynamic control of electricity flows)
- and the sources of flexibilities (RES, demand-response, grid and new storages).

It addresses all system requirements to capture the synergies proposed by the different solutions in order to avoid stand-alone solutions that might be less efficient in terms of overall efficiency. Four demonstrations led by Transmission System Operators (RTE, REE, TERNA and ELES) address different flexibility solutions and services:

- Grid-connected grid-forming
- New hybrid and modular storage solution with the capability to offer multiple system services
- Near real time cross border exchanges between Italy and Slovenia
- A smart energy management system including Dynamic Thermal Rating, demand response and RES in the South of Italy

OSMOSE expected impacts

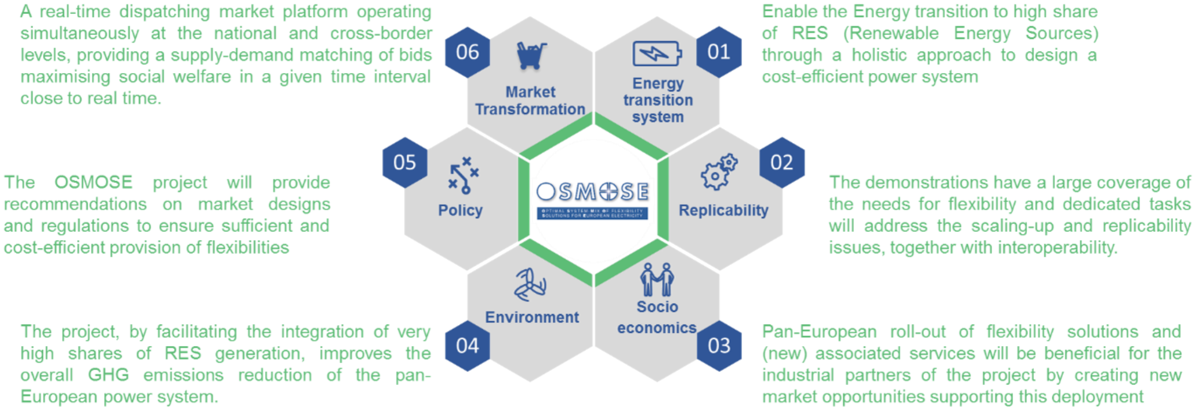


Figure 34 OSMOSE expected impacts

Related findings

Flexibility can be illustrated as an umbrella term covering various needs in the power system. When trying to identify the most crucial ones, one may mention:

- adequacy - ensuring long term equilibrium between power supply and demand
- power transmission - allowing power to flow between supply and demand, while respecting physical and operational limits on flows between buses1
- reactive power control - keeping the bus voltages within predefined limits
- frequency stability - ensuring frequency stability in the event of a large unforeseen imbalance
- voltage stability – ensuring voltage stability in the event of insufficient reactive power infeed

Short-, medium- and long-term flexibility for adequacy and frequency stability all serve the same purpose: balancing supply with demand in energy systems with high shares of variable renewables. Yet, they differ in the time available for balancing and the energy required to achieve the balance as displayed in the following figure (Figure 1). While short-term flexibility has to provide ancillary services on very short notice, compared to long-term seasonal storage the amount of energy required is small. The opposite applies for long-term flexibility.

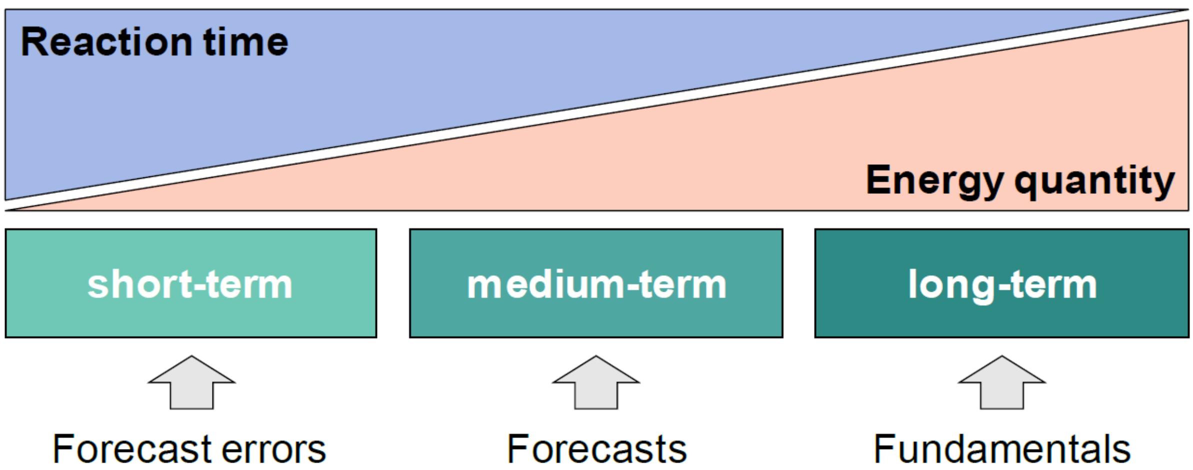


Figure 35 Typology of flexibility requirements

Source: OSMOSE D1.2 “Flexibility cost and operational data outlook”, May 2019, available at: https://www.osmose-h2020.eu/download/d1-2-flexibility-cost-and-operational-data-outlook/

Technological solutions of OSMOSE demonstrators

A comprehensive description of technologies being developed by OSMOSE demonstrators can be consulted on the internal companion report on the subject. Figure 2 presents the main findings regarding market synergies and market barriers identified on that report.

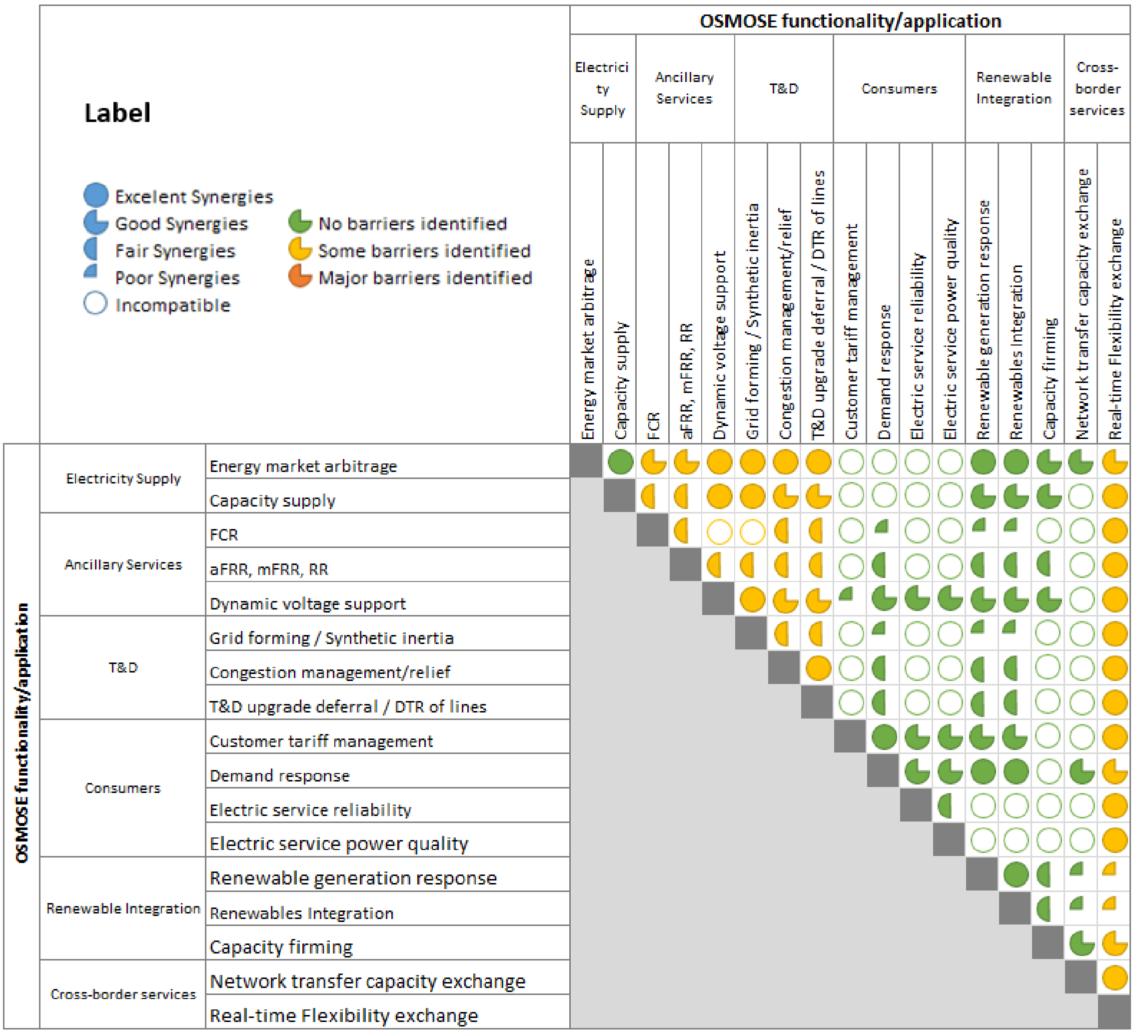


Figure 36 Synergies and market barriers faced by OSMOSE demos

Source: OSMOSE D2.2 "Candidate market mechanisms and regulatory frameworks", May 2019, available at: https://www.osmose-h2020.eu/download/d2-2-candidate-market-mechanisms-and-regulatory-frameworks/

Flexibility KPIs

This project proposes a list of quantitative and qualitative key performance indicators (KPIs) that will allow comparing different market design alternatives. The goal of this comparison is to rank different market designs regarding their performance for providing flexibility needs given a massive integration of RES. For each aspect of markets, KPIs have been proposed in the previous tables. A definition and explanations are then given in Deliverable 2.1.2 "KPIs measuring the value of flexibility", that is available at the project website[77], brings a clear understanding of the calculation and the use of each indicator. The process has been to identify a list of several indicators that would allow comparing different market designs.

Functionalities and services for the power system

D4.178 compiles a detailed description of each of the functionalities that have been identified as essential, and therefore required for the Multi-Component Flexibility Solution (MCFS) to fulfil the expected use cases. The following table shows the compatibility matrix between the different functionalities.

[77] Available at: https://www.osmose-h2020.eu/wp-content/uploads/2021/03/OSMOSE_WP2_KPIs-measuring-the-value-of-flexibility.pdf
[78] Available at: https://www.osmose-h2020.eu/download/d4-1-comprehensive-report-on-functionalities-and-services-for-the-power-system/

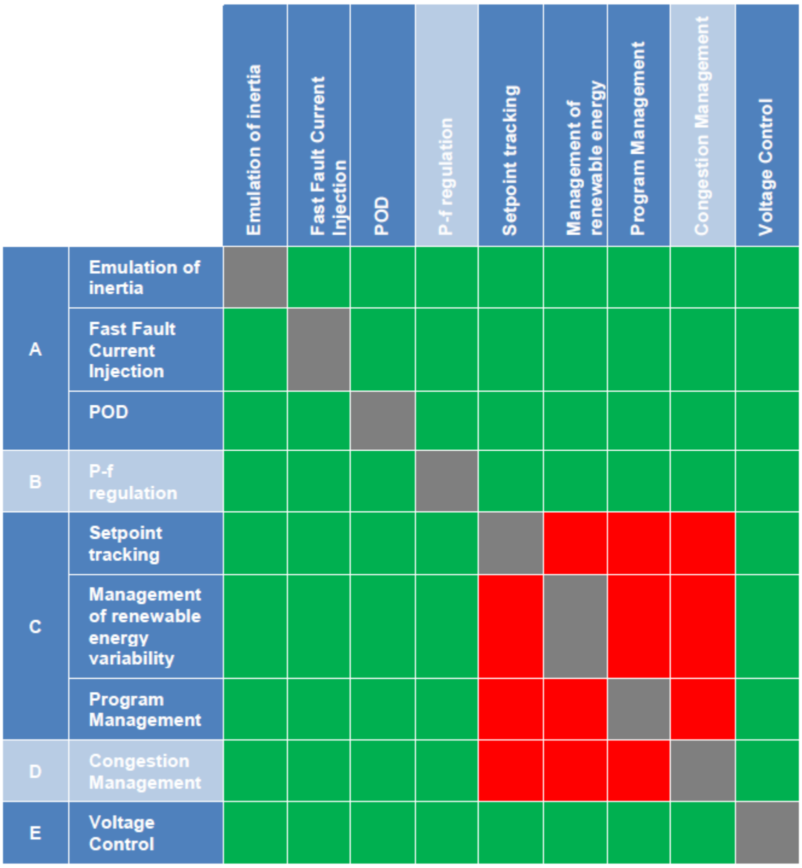


Figure 37 Compatibility matrix between the different possible functionalities

In the following table main parameters to define the functionalities/services of the MCFS are shown:

Table 10 Characterisation of expected functionalities

	Emulation of inertia	P-f regulation	Setpoint tracking	Management of renewable energy variability	Program Management	Voltage Control	Congestion Management
No. of cycles/year	<10	continuous	continuous	>100	continuo	continuous	<10
Duration of the duty cycle	minutes	continuous	n.a.	minutes	n.a.	continuous	minutes
Initial energy content	SOC= 100%	SOC= 50%	n.a.	SOC= 50%	n.a.	n.a.	SOC = 0%
End energy content	SOC=0	20%<SOC <80%	n.a.	0%<SOC< 100%	n.a.	n.a.	SOC 100%
Maximum value of active power output	100% of Pn_n	100% of Pn_n	100% of Pn_n	100% of Pn_n	100% of Pn_n	n.a.	0
Maximum value of active power input	n.a.	100% of Pn_n	100% of Pn_n	100% of Pn_n	100% of Pn_n	n.a.	100% of Pn_n
Velocity of changes in the active power values	Instantaneous change after event	Operation in continuous mode	Each minute	Each minute	Every 10 minutes	n.a.	Each minute
Speed of change between states of active power injection/absorption	n.a.	Maximum possible ramp-rate	Maximum possible ramp-rate	Maximum possible ramp-rate	Maximum possible ramp-rate	n.a.	n.a.
Maximum partial energy output	ΔSOC=100%	ΔSOC=30%	ΔSOC=100%	ΔSOC=100%	ΔSOC=100%	n.a.	n.a.
Maximum partial energy input	n.a.	ΔSOC=30%	ΔSOC=100%	ΔSOC=100%	ΔSOC=100%	n.a.	ΔSOC=100%
Maximum value of reactive power output	n.a.	n.a.	n.a.	n.a.	n.a.	100%	n.a.
Maximum value of reactive power input	n.a.	n.a.	n.a.	n.a.	n.a.	100%	n.a.
Velocity of changes in the reactive power values	n.a.	n.a.	n.a.	n.a.	n.a.	Maximum reactive ramp-rate.	n.a.
Speed of change between states of reactive power injection/absorption	n.a.	n.a.	n.a.	n.a.	n.a.	Maximum reactive ramp-rate	n.a.
RESOURCE INVOLVED	SCAP, FLYWL, BATTERY	BATTERY	BATTERY	BATTERY	BATTERY	STATCOM SCAP BATTERY	BATTERY

Detailed description of each of the functionalities required for the MCFS to fulfil the expected use cases are addressed. There is a special emphasis on how the described functionalities are intended to interact, both among them, as well as in relation to the power grid itself.

L. FLEXITRANSTORE Project

Project basic information

Main goal: FLEXITRANSTORE (An Integrated Platform for Increased FLEXIbility in smart TRANSmission grids with STORage Entities and large penetration of Renewable Energy Sources) aims to contribute to the evolution towards a pan-European transmission network with high flexibility and high interconnection levels. This will facilitate the transformation of the current energy production mix by hosting an increasing share of renewable energy sources. Novel smart grid technologies, control and storage methods and new market approaches will be developed, installed, demonstrated and tested introducing flexibility to the European power system. FLEXITRANSTORE will promote increased cross-border electricity flows using the valorization of flexibility services. The project takes both a national and a regional approach, acknowledging the need to seamlessly integrate national markets, particularly in the South Eastern European network, which still lacks the high interconnectivity that the rest of the European network has.

List of partners: ED(Coordinator), ICCS, TUS, UCY, BME, LUA, EMAX, WING, ABG, JEMA, GEF, SCHN, SWE, C&G, STER, SC, IPTO, CTSO, R&D NESTER, OST, CEZ, ELJ, EAC, IBEX, VPP, CERA, CHALM, IEIT, COGEN.

Source of funding: European Union's Horizon 2020 research and innovation programme under grant agreement Nº 774407.

Duration: 2017-2022

Webpage: http://www.flexitranstore.eu/

Project learnings

The FLEXITRANSTORE project is in line with the ETIP-SNET 10 year R&I Roadmap and the ENTSO-E R&I Roadmap 2017-2026, which identify the main evolutions of the power systems in the decades to come. These evolutions include an ever-increasing penetration of Distributed Renewable Sources and controllable Distributed Loads. The objectives of FLEXITRANSTORE are complementary to the R&I Roadmaps and will impact both new and existing market participants. FLEXITRANSTORE will provide the necessary technical and market advancements to facilitate the safe and seamless transition towards this new era.

FLEXITRANSTORE will develop a next generation Flexible Energy Grid (FEG) which will be integrated into the European Internal Energy Market (IEM), through the valorization of flexibility services. This FEG addresses the capabilities of a power system to maintain continuous service in face of rapid and large swings in supply or demand. Thus, a wholesale market infrastructure and new business models within this integrated FEG should be upgraded to network players, offering incentives to new ones to join, while demonstrating new business perspectives for cross-border resources management and energy trading.

FLEXITRANSTORE will transform the European Power System through interventions that target the whole Energy Value Chain. The following figure presents the 8 demonstrators of the project.

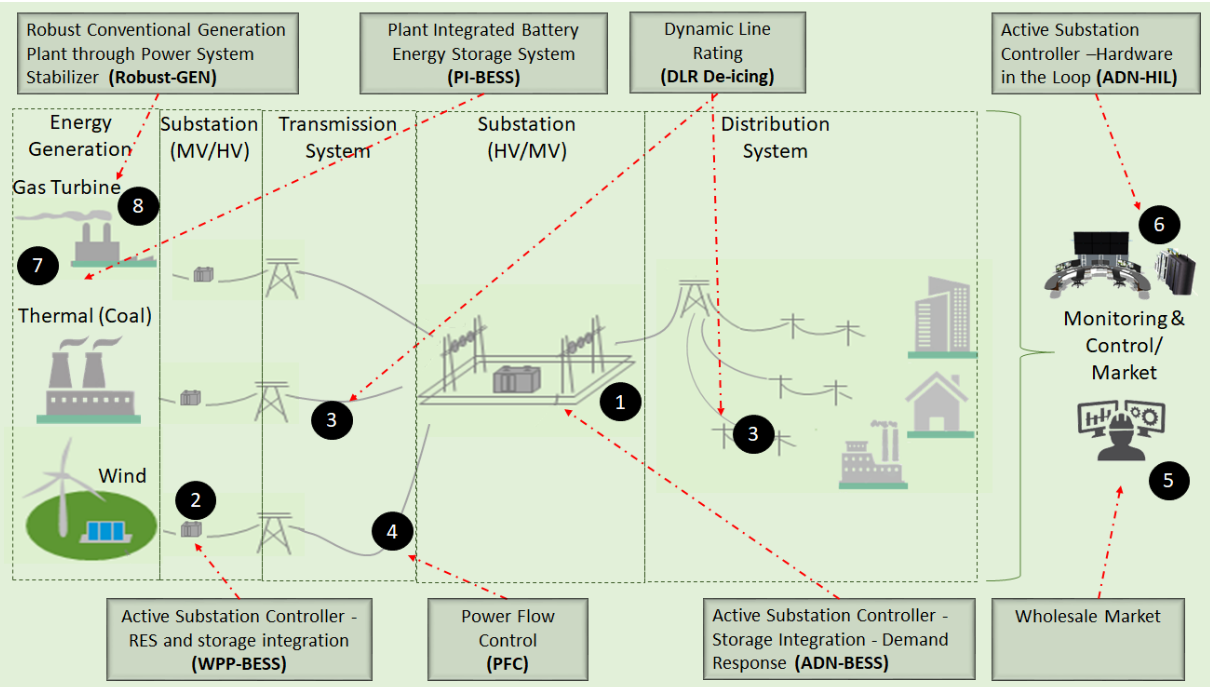


Figure 38 Flexitranstore project demonstrations

FLEXITRANSTORE OBJECTIVES

Renewable energy is facing increasing popularity due to the unquestionable advantages that it introduces to society. Renewable energy facilitates system decarbonization, long-term energy security and its distributed nature allows the expansion of energy access to new remote energy consumers.
An 100% integration of RES to the power system remains a challenge, though, due to the intermittent, variable and unpredictable production, which also poses as a problem for the energy market, in terms of dynamic pricing, and flexible trading among participants.
Following the current trends and EU regulations FLEXITRANSTORE has identified two main strategic objectives:

- To enhance and accelerate the integration of renewables into European Energy systems.
- To increase cross-border electricity flows across Europe.

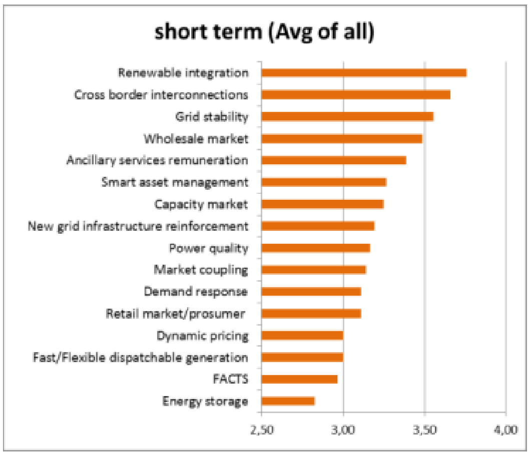
A number of project specific objectives has also been specified, which will facilitate the fulfillment of the strategic objectives and pave the way towards a sustainable energy future.

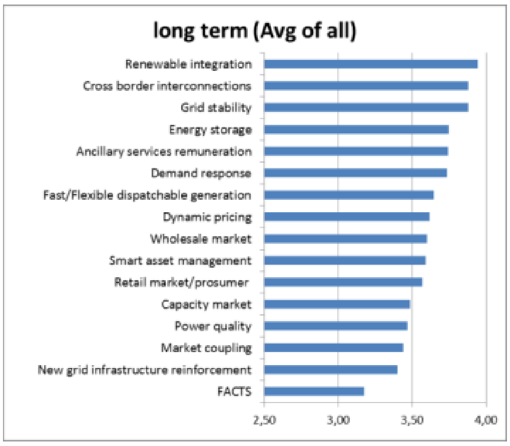
- To increase flexibility across the energy industry value chain by integrating BESS supporting the provision of ancillary services by RES at points such as: the TSO/DSO interface or wind farms and gas turbine plants.
- To increase flexibility in the transmission grid by integrating Power Flow Controllers aiming to perform congestion management and redirection of power flows, by developing Dynamic Line rating methods for de-icing of power lines purposes and by developing efficient novel controllers for active substations at the TSO/DSO border and wind power plant connections to the HV network.
- To increase flexibility in the distribution grid by developing and implementing novel demand-response mechanisms, thus creating new market actors and opportunities.
- To increase flexibility of conventional generators by installing novel Power System Stabilizers, restoring low rotational system inertia and by simulating grid behavior after major events on a representative grid model which will allow better insight grid dynamics and stability.
- To increase flexibility within the wholesale electricity markets, by the development of an integrated market platform, based on an enhanced EUPHEMIA market model, which valorizes flexibility services through improved operations, demand response, enhanced generator services, energy storage or a smarter infrastructure.

Related findings. Looking back to the outcome of FLEXITRANSTORE survey, great feedback is provided on the prioritization of electricity grid and market topics set in various European countries. One interesting remark is that stakeholders rank as highly relevant certain topics which are actually the result of various reforms, while at the same time these “reforms” are considered as less relevant. For example, ‘market coupling’ is considered less relevant than ‘cross border interconnections’ while both they are very much related. Accordingly, ‘renewable integration’ is top–ranked in all time horizons, while ‘energy storage’ which assists/promotes greatly RES integration, is ranked much lower.

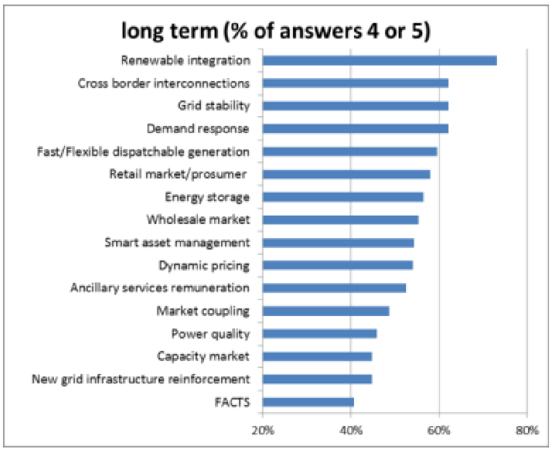
In this sense, it can be concluded that the cause-and-effect relation of innovation in grid and market (i.e. energy storage, FACTS, market coupling, dynamic pricing etc) is not crystal clear to stakeholders with the profound topics of energy transition i.e. Renewable Integration, Cross Border Interconnection, Grid Stability. In deliverable 2.3[79], a strategic decision-making method was presented to ‘channel’ the effects of innovation to the power system operation through specific KPIs which are elaborated in section 3, having the common characteristic of flexibility improvement. Thus, the FLEXITRANSTORE approach comes to relate the cause and effect of innovations presented through the project. It has been ‘triggered’ by CBA tools for smart grid and energy storage projects, sponsored by the American Recovery and Reinvestment Act, Smart Grid Investment Grant program and Smart Grid Demonstration program. These approaches are developed for the US electricity markets with different reimbursement schemes for grid services depending on the various country regions.

[79] D2.3 “Strategic decision making for power system flexibility by innovation integration”, available at: http://www.flexitranstore.eu/sites/default/files/publications/Flexitranstore%20-%20D2.3.pdf





Average value of relevance, according to stakeholders' answers to FLEXITRANSTORE questionnaire, on critical topics related to flexibility, in short (1-5 years) or long (6-10 years) horizon



Percentage of number with high relevance, according to stakeholders answers to FLEXITRANSTORE questionnaire, over total answers on critical topics related to flexibility, in short (1-5 years) or long (6-10 years) horizon

Figure 39 Flexitranstore survey results

Lately, TenneT Netherlands introduced a relevant software platform, which models the business case of a grid-connected energy storage projects, taking into account technical characteristics, costs and revenues of a project, and combines them into a business cashflow model[80]. This is an excellent tool for energy stakeholders in their understanding of the business case of an energy storage project. Standing on the position of the grid operators, FLEXITRANSTORE identified inflexibilities, the flexibility resources stemming from physical characteristics of the power system (b) uses the market operation characteristics (c) evaluates the innovation technology characteristics of the power system upgrade solutions and (d) provides a solution that improves the level of renewable energy share, sustain high grid reliability and resilience, and generally perform high values of a specific set of related KPIs. This approach can be customized for the market characteristics of the SEE countries participating, where flexibility services in electricity markets are still in an infant state.

The aforementioned elements (a)-(d) formulate a kind of "3-Dimensional space" for Strategic Decision Making on use-case scenarios of future power systems operation, the SDM approach. An illustration of this task 2.5 proposed approach is illustrated in the following figure.

[80] "TenneT Storage Tool User Guide V1.0", Ecofys 2018, commissioned by TenneT.

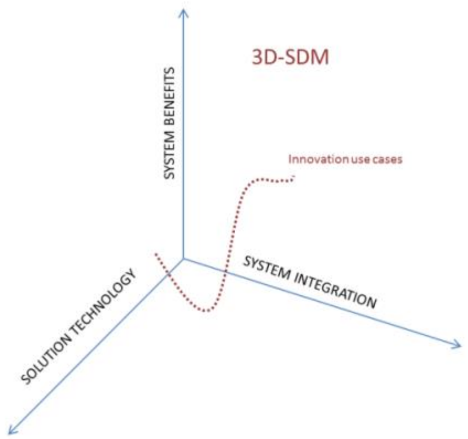


Figure 40 Illustrative representation of the SDM approach proposed by FLEXITRANSTORE, showing the various aspects affecting the formulation of innovation use case to be evaluated

Key Performance Areas (KPAs) can be quantified through specific KPIs, as indicated in the following tables:

Table 11 Proposed KPIs to be used in the FLEXITRANSTORE project

No	System benefits (KPAs)	Proposed KPIs of FLEXITRANSTORE
1	*Renewables integration*	- Reduction in renewable curtailment on existing generation facilities - Cost of enabling new renewable interconnections relative to conventional solutions - Share of electricity generated from renewable sources - Increased RES and DER hosting capacity - Reduced energy curtailment of RES and DER - Avoid redispatching
2	*Congestion reduction*	- Reduction in redispatching - Increased network capacity - Maximum transfer capacity - RES Energy unleashed - Reduced Congestion Costs
3	*Flexibility indices improvement*	- IRRE, FIX - Capacity of reserves increase - -Maximum hourly ramp of residual load - -Additional capacity (NTC) in relation to existing cross-border capacity - Grid expansion deferral by applying peak-shaving’
4	*Improving Reliability and Quality of Supply*	- LOLE, LORP, -EENS - Additional adequacy margin - VOLL, - Average Hourly Load Not r
5	*Improved competitiveness of the electricity market*	- Type of energy pricing/market products - Market services remuneration - Number of market actors per activity - Concentration ratio (CR)

Table 12 Mapping of System Benefits with different demonstration and tested technologies of FLEXITRANSTORE

Demo	Technology	Benefits				
		RES integration	*Congestion reduction*	*Flexibility indices improvement*	*Improving Reliability and Stability*	*Improved competitiveness of the electricity market*
1	Active Distribution Node	√		√	√	√
2	Battery Energy Storage at Wind Power Plant	√	√		√	√
3	Dynamic Line Rating			√	√	
4	Power Flow Controller	√	√	√		
5	Adapting wholesale market approach	√		√		√
6	Advanced controllers for grid services				√	
7	BESS for combined cycle power plant	√		√		√
8	Advanced control for flexible synchronous generation				√	

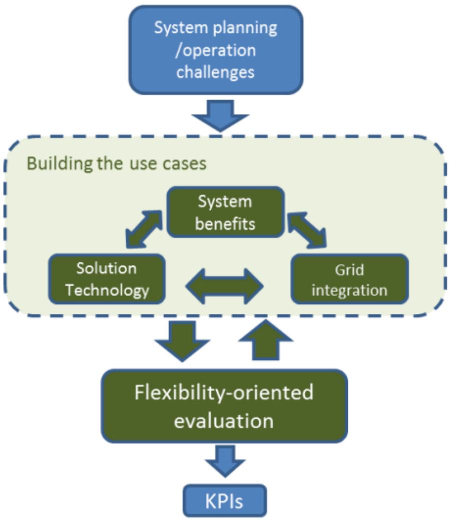


Figure 41 Flowchart for strategic decision making through innovation integration

The strategic decision-making method presented in the previous figure has been adapted to cover five specific use cases of the technologies, focusing on various aspects of their impact on the electricity networks. The use cases presented here are aligned with the business use cases explored in the FEG platform and will contribute to the integration of FEG architecture. The basics of these use cases will be presented here while in great detail are analysed on the full deliverable 2.3.

Use case 1: BESS integration in Cyprus. An evaluation of BESS impact on the Cyprus power system is being conducted for various integration scenarios, building on the flexibility assessment platform of task 2.4 and the strategic decision making method basics and flow presented in the previous paragraphs. Specific services and operational patterns for the BESS have been considered and flexibility and cost KPIs have been calculated to illustrate the optimal scenario, in the system planning horizon of the following 5 years.

Use case 2: RES integration in Greece. An indicative use case of RES integration challenges with the Greek RES and demand characteristics is being presented e. The BESS integration is been considered for improving the regulating reserves of the network , and KPIs regarding operation cost, reserve requirements, reliability and RES penetration are being calculated, showing the impact of the BESS on system performance.

Use case 3: Congestion relief with power flow controller for facilitating RES project. Alternative innovative solutions to conventional substation upgrade for improving RES integration are being provided in use case 3 through the Power Flow Controllers. The Power Flow Control innovative solutions (namely SmartWires products) is weighed against conventional grid upgrades or a phase shifting transformer in various Key Performance Areas and score as a preferable solution.

Use case 4: Enabling Challenging Construction & Reduce Generation Costs. The facilitation of the re-conductoring project with low additional capacity needed is being presented in a use case implementing Power Flow Control devices. The alleviation of congestion through alternative routes facilitates the safe implementation of the reconductoring project and security of supply with no additional costly generation.

Use case 5: Innovation technology as an alternative to conventional transmission upgrade solutions. Another use case of a utility facing a combination of transmission challenges is being presented: new RES capacity to be connected, load growth and phase-out of thermal capacity constitute a difficult situation. Specific strategies of modular deployment are being analysed. It is shown that modular PFC accounts for uncertainty in future grid development as an overall better business case than traditional options like reconductoring. The optionality to augment PFC deployment size at an existing installation in case the needs increase at that location, allows utilities to defer high-cost decisions to a later date.

Deliverable 2.4 “Flexibility assessment study for the SEE region: Greece, Bulgaria, Cyprus”[81], provides advanced flexibility assessment studies in the SEE countries of Greece, Bulgaria and Cyprus are presented, elaborating in certain specific scenarios of system operation and RES integration.

Flexibility Assessment Tool

Objective:

- Review international trends and challenges in grid flexibility and assess flexibility issues in the South East European (SEE) region
- Study the flexibility requirements and resources in Greece, Bulgaria and Cyprus

[81] Available at: http://www.flexitranstore.eu/sites/default/files/publications/Flexitranstore%20-%20D2.4.pdf

- Leverage the feedback of major stakeholders in Europe through extensive survey and respective analysis of the responses, in order to address real needs
- Develop an analytic methodology for flexibility assessment aligned with current TSO adequacy assessment, evaluating short-term needs of system balancing to long-term planning
- Provide a pathway of strategic decision making through CBA approaches worldwide and specific Key Performance Areas and Indices (KPAs and KPIs)
- Elaborate on future scenarios of joint operation in the SEE region with forecasting uncertainty modelling and more interconnection capacity

Achievement:

- Develop an upgraded flexibility adequacy assessment methodology, with a stepwise approach from IEA FAST to hourly simulations, for calculating specific flexibility indices such as Insufficient Ramping Rate Expectation, Flexibility Residual.
- Study in detail the net-load forecast errors and highlight the time periods of greater deviations and need for flexibility resources.
- Implement the methodology in Greece, Cyprus and Bulgaria, in close cooperation with the national TSOs and analyse the future flexibility requirements of the respective power systems.
- Analyse the CBA methodologies applied worldwide and how they evaluate the impact of new grid upgrade project for system operation.
- Leverage important features of these methodologies and propose a new strategic decision-making approach for innovation technology integration into the transmission networks.
- Propose five specific Key Performance Areas to be evaluated in the method and respective set of KPIs to quantify the impact of new technology into the network operation.
- Link the strategic decision-making approach with the flexibility adequacy simulation platform in order to provide an upgraded toolbox for new technology promotion in planning studies.
- Present and analyse five use cases of integrating new technologies solutions related with FLEXITRANSTORE demonstrations.
- Highlight specific benefits of the solutions in the use cases, paving the way for further studies in WP13 of scalability and replicability evaluation.

Flexible Energy Grid Architecture (FEG)

Following the Methodological Approach, the purpose of which was to identify all the relevant components and functionalities that FEG platform could provide to the operators and the involved actors of the energy market, the FLEXITRANSTORE project focused on the design and development of an IT platform (or toolbox) that will be the facilitator all functions to be offered to the final end-user. For this reason, it is important to present the reference architecture of the FEG platform from the ICT point of view and the connected perspective of the flexibility providers. The architecture includes the definition of the main FEG platform components and how they communicate to meet interoperability, reliability, security and data protection requirements. All demo-related activities are currently in the integration and testing phase with FEG, as will be explained below. The FEG Platform is designed to provide a powerful set of tools to players in the Energy community. It is envisioned as a different approach and a step ahead in flexibility, scalability, security and reusability.

In general terms, the proposed architecture for the FEG platform is firstly subdivided in two distinct main components. The first one presents the FEG Central Component that acts as the global registry of FEG installations and integration hub, and the second one is the FEG local component that represent the ready-to-use toolbox - installed within System Operators' and Flexibility Providers. Secure data handling requirements have been considered.

The open architecture of the FEG Platform provides ease of integration within the operators' software environments and facilitates bi-directional communication with external systems, thus adding a high degree of flexibility and adaptability even in extreme brownfield situations. The following figures provide an overview of the FEG platform architecture.

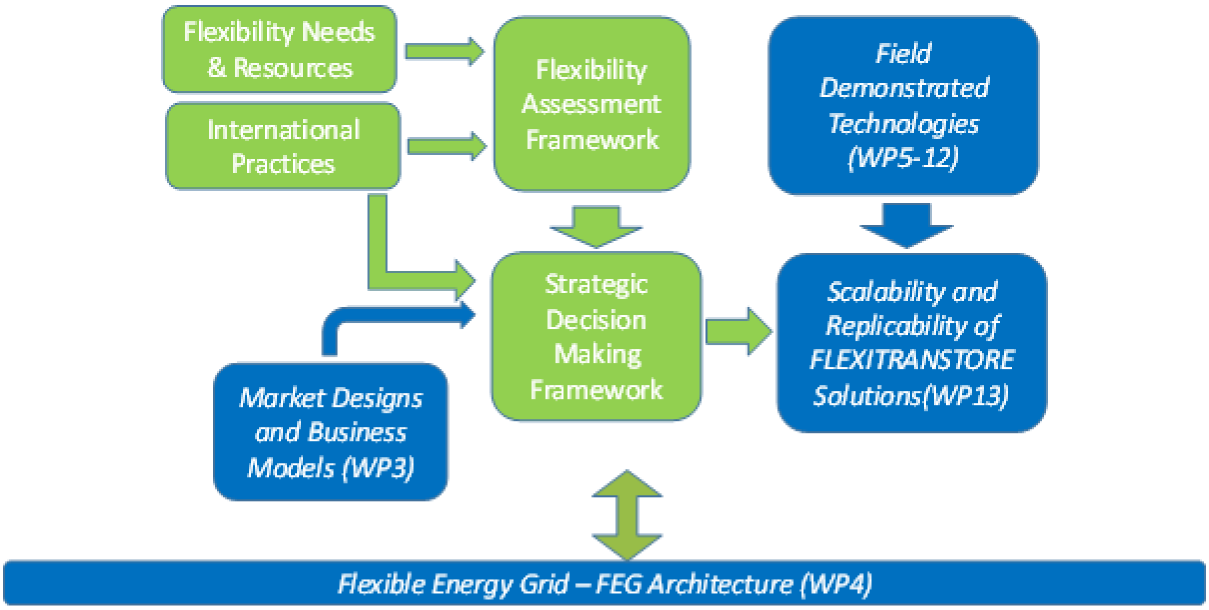


Figure 42 FEG Platform Architecture

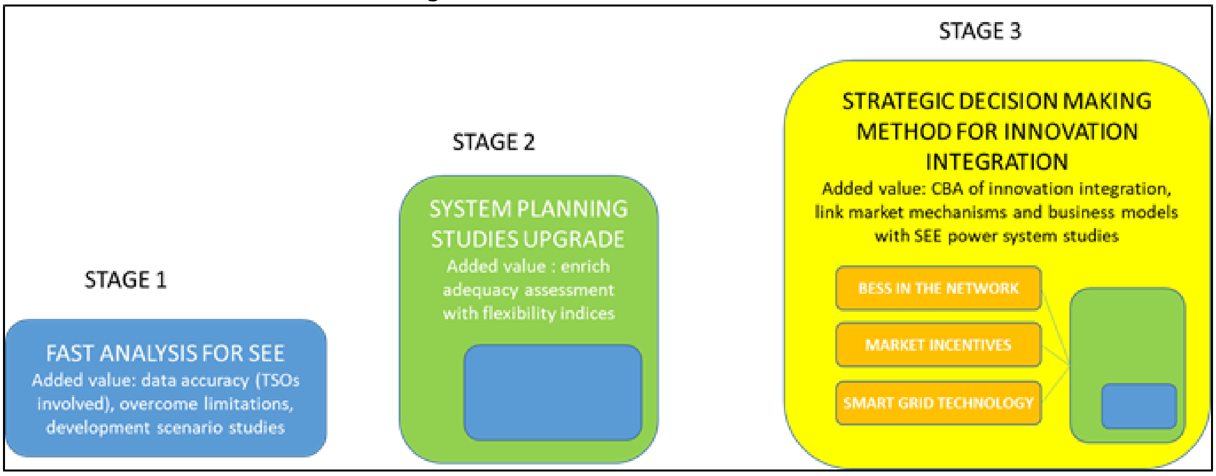


Figure 43 FEG Architecture Stages Description

M.Equigy Pilot Project

Project basic information

Main goal: In this pilot project we develop a concept for systematic coordination between the TSO and DSOs with respect to the use of distributed flexibility resources controlled by a third-party aggregator. Note that even though ewz is both a DSO and aggregator in the Swiss ancillary services market, the two roles are considered distinctly in the pilot. The concept covers both the planning and operation phases: (i) Flexibility sharing between a TSO and DSOs in the operational planning stage creating a transparent nodal view on available flexibility per grid node (ii) Coordinated activation of flexibility resources among the TSO and DSOs in operation.

Furthermore, the pilot project aims at implementing the coordination concept on the Crowd Balancing Platform of Equigy, a Joint Venture of European TSOs that develops a technology to facilitate access of distributed energy resources to balancing and redispatch markets. Equigy is envisioned as the communication and data storage layer among the TSO, DSOs, aggregators, and flexible resources. Depending on the complexity, the TSO-DSO coordination module can be either an external software component or integrated within the Equigy platform (partially or completely). The long-term vision is to establish the TSO-DSO coordination on a market-based allocation of the available flexibility.

List of partners: Swissgrid and ewz (in collaboration with Equigy and Venios)

Source of funding: internal

Duration: 2021 – 2024

Webpage:
https://www.swissgrid.ch/en/home/newsroom/newsfeed/20210603-01.html
https://www.swissgrid.ch/en/home/newsroom/dossiers/crowd-balancing-platform.html

Project learnings

An increasing number of small-scale flexible resources are connected to the distribution grid, such as residential batteries, charging stations for electric vehicles, and heat pumps. In principle, the flexibility of these resources can be used to provide services either to the TSO or to the local DSO. In Switzerland, there already exist aggregations of such resources that provide ancillary services to Swissgrid or local services to DSOs. Today, no systematic mechanism is used to share the available flexibility between the system operators. On the one hand, the DSOs typically have bilateral agreements with the owners of flexibility resources and activate them according to their needs, but without procuring the flexibility as a service in a market setting. On the other hand, the TSO typically procures ancillary services in a market and activates them through aggregators, but without considering the status and constraints of the distribution grid where they are connected.

Typically, an aggregator providing ancillary services to the TSO aligns with the local DSO only at the prequalification stage. Specifically, the aggregator informs the DSO that it intends to control resources in the DSO grid for TSO purposes, and the DSO approves or rejects this request. However, this is a one-time, static alignment process which can lead to inefficient utilization of the available flexibility resources in operation. In this pilot project we develop a concept for systematic coordination between the TSO and DSOs with respect to the use of distributed flexibility resources controlled by a third-party aggregator. Note that even though ewz is both a DSO and aggregator in the Swiss ancillary services market, the two roles are considered distinctly in the pilot. The concept covers both the planning and operation phases:

- Flexibility sharing between a TSO and DSOs in the operational planning stage creating a transparent nodal view on available flexibility per grid node.
- Coordinated activation of flexibility resources among the TSO and DSOs in operation.

Furthermore, the pilot project aims at implementing the coordination concept on the Crowd Balancing Platform of Equigy[82], a Joint Venture of European TSOs that develops a technology to facilitate access of distributed energy resources to balancing and redispatch markets. Equigy is envisioned as the communication and data storage layer among the TSO, DSOs, aggregators, and flexible resources, as shown in Figure 44. Depending on the complexity, the TSO-DSO coordination module can be either an external software component or integrated within the Equigy platform (partially or completely).

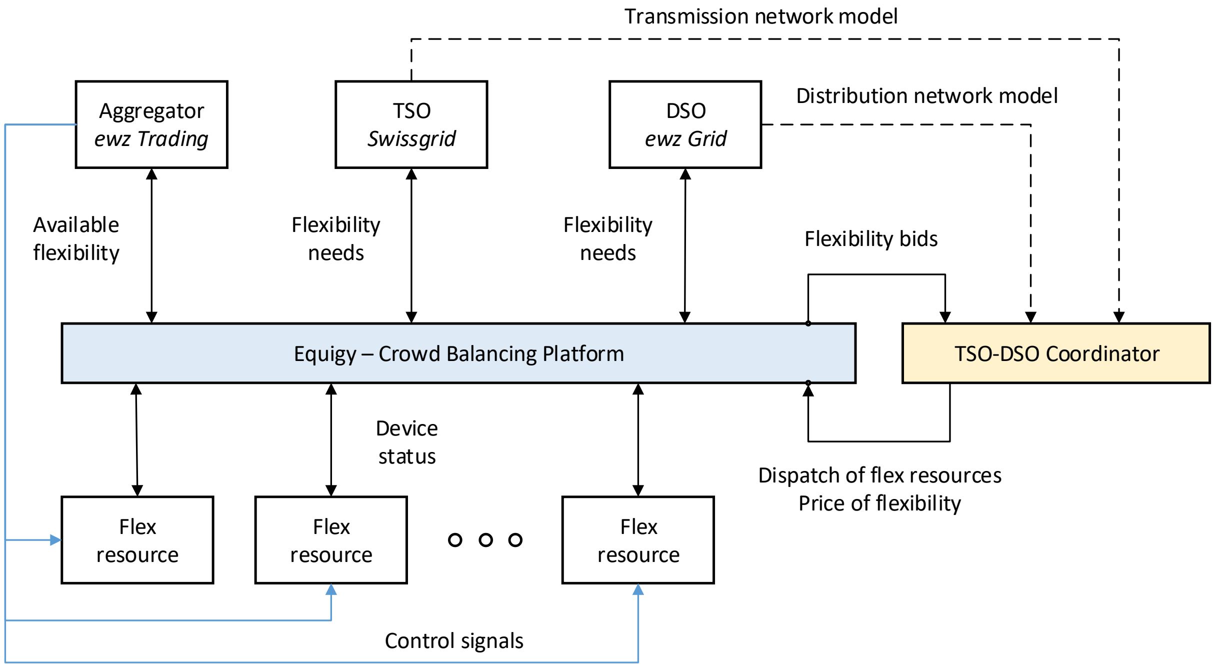


Figure 44 Visualization of roles and data flow through the Equigy platform and the various players

The long-term vision is to establish the TSO-DSO coordination on a market-based allocation of the available flexibility. The idea is that aggregators offer aggregated flexibility to a market platform and a mathematical optimization algorithm allocates the flexibility resources to the TSO or DSO services with the highest economic value at any point in time, while ensuring that transmission and distribution network constraints are satisfied. Such a common TSO-DSO flexibility market can be implemented with either a centralized, i.e. common

[82] https://equigy.com/

optimization between TSO and DSOs, or a decentralized architecture for flexibility sharing, where only the relevant information at the interface nodes between DSOs and the TSO is exchanged.

The project is structured into various phases. In the first phase, we develop a simpler rule-based approach for the TSO-DSO coordination which consists of two elements:

- Local flexibility model: the DSO has priority in deciding which part of the available flexibility should be kept for its own needs and which can be made available to the TSO.
- Traffic light model: the DSO can block activations of flexible resources for TSO purposes, if these would lead to violations in the distribution grid (and vice versa).

From the TSO point of view, the first phase of the project will focus on the products of the Swiss Integrated Market, namely tertiary control energy and international zonal redispatch. ewz will focus on using flexibility for congestion management in the distribution grid. The concept includes various business processes related to registration of flexible resources, bidding of flexibility, evaluation of the traffic light model, and activation of resources for TSO or DSO services, as shown in Figure 45. The feasibility of the concept will be demonstrated by testing it using one or more physical flexibility resources connected to the distribution grid.

The first phase of the project officially started in April 2021 and will run until August 2022, whereas the subsequent phases are expected to run from the end of 2022 to 2024. Upon its successful completion, this pilot project will be a key milestone with high importance for Switzerland due to the large number of DSOs and increasing amounts of distributed energy resources. Built on Equigy, the TSO-DSO coordination concept can become the role model for similar approaches in other European countries.

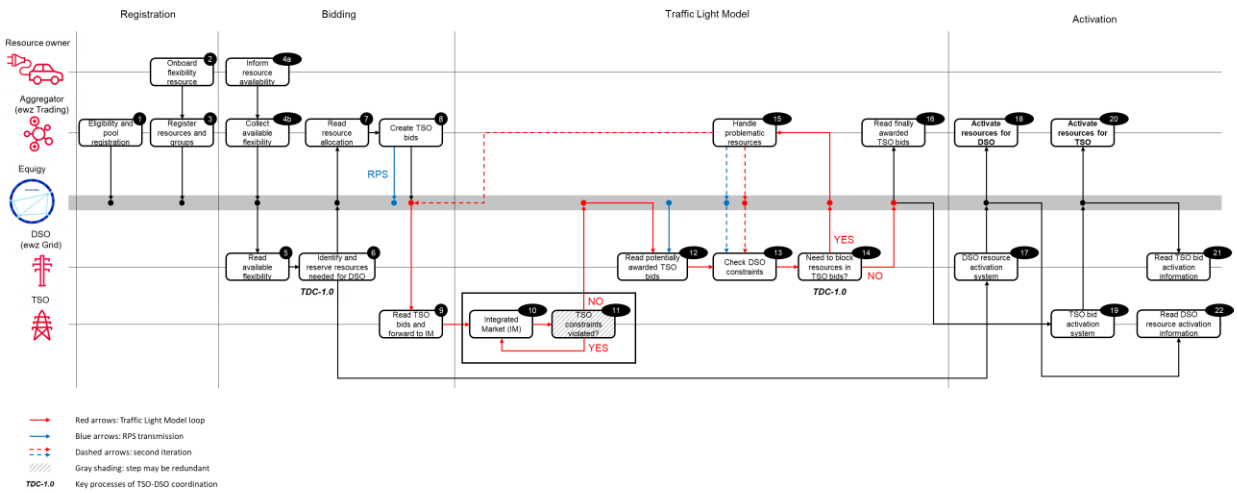


Figure 45 Business processes of the TSO-DSO coordination concept.

N. TDFlex Project

Project basic information

Main goal: The project investigates whether it is techno-economically feasible and beneficial to exploit the aggregated flexibility at the TSO-DSO substation provided by the distributed energy resources (DERs) connected to the distribution network for transmission-level network and system benefits: (i) voltage support [*If there is a voltage violation in the TSO grid, is it technically and economically feasible to solve it with PQ-flexibility at the TSO-DSO substation? Compared to (1) use of conventional generators by TSO and (2) technology that can be deployed at the TSO-DSO substation (BESS, synchronous condenser etc.)*], (ii) congestion management [*If there is a congestion in the TSO grid, is it technically and economically feasible to solve it with PQ-flexibility at the DSO substation? Compared to traditional re-dispatch by TSO.*], and (iii) balancing services [*Can the aggregated flexibility be competitively offered in ancillary markets day-ahead or intraday? Even if they are not competitive, for example, in providing reserve, can the aggregated flexibility relieve some generators so that these generators can produce cheap energy instead of providing reserves?*].

List of partners: Research Centre for Energy Networks at ETH Zürich (observing partners include ewz, Repower, Swissgrid)

Source of funding: Swiss Federal Office of Energy (SFOE) and Swiss Association for Energy and Network Research (SGEN)

Duration: 2019 – 2021

Webpage: https://www.fen.ethz.ch/activities/system-operation/tdflex.html

Project learnings

The project investigates the following network and system benefits to determine whether it is techno-economically feasible and beneficial to exploit the aggregated flexibility at the TSO-DSO substation provided by the distributed energy resources (DERs) connected to the distribution network: (i) for congestion management within the TSO grid as well as at the TSO-DSO substation, (ii) for voltage support to the transmission system provided at the TSO-DSO substation and (iii) for balancing services in transmission system. By partnering with local utilities in Switzerland, this project examines the achievable benefits of a stronger TSO-DSO interaction in Switzerland.

General approach consists in using reduced representation of the DSO's grid capability by means of estimating "flexibility boundaries/areas" at the TSO-DSO interfaces and computing the associated cost of providing flexibility. Once the flexibility areas and associated costs are estimated, this capability is modelled as a "pseudo generator" (or flexibility generator) at each TSO-DSO substation for each transmission service. It is assumed that the identification of the flexibility area is performed by the utility or an aggregator either day-ahead or intraday look-ahead (e.g., 15-min-/60-min ahead). The technical and economic potentials of the flexibility at the TSO-DSO interface substation are compared to conventional methods in the following transmission services:

- voltage support [*If there is a voltage violation in the TSO grid, is it technically and economically feasible to solve it with PQ-flexibility at the TSO-DSO substation? Compared to (1) use of conventional generators by TSO and (2) technology that can be deployed at the TSO-DSO substation (BESS, synchronous condenser etc.)*],
- congestion management [If there is a congestion in the TSO grid, is it technically and economically feasible to solve it with PQ-flexibility at the DSO substation? Compared to traditional re-dispatch by TSO], and
- balancing services [*Can the aggregated flexibility be competitively offered in ancillary markets day-ahead or intraday? Even if they are not competitive, for example, in providing reserve, can the aggregated flexibility relieve some generators so that these generators can produce cheap energy instead of providing reserves?*].

The candidate flexibility providers in the distribution network are selected as follows: distributed renewable energy resources, particularly solar PV, battery energy storage systems, electric heat pumps, EV charging, and conventional electric demand. Figure 46 demonstrates the “flexibility area” concept for a given distribution grid. It is noted that <u>at every time instant</u>

- the operating point of the system, observed at the TSO-DSO interface substation,
- the available maximum solar PV generation,
- the status of the electric heat pumps,
- the status of the EV charging and the available number of EVs,
- the state of charge (SoC) of the BESS, and
- the amount of the electric demand

Thus, the “flexibility area” at the TSO-DSO interface substation is time-dependent and the shape will vary (size and type) at each time instant as shown in Figure 46. Note that the operating points at different time instants are shifted to the origin to be able to conveniently compare the size of the flexibility area.

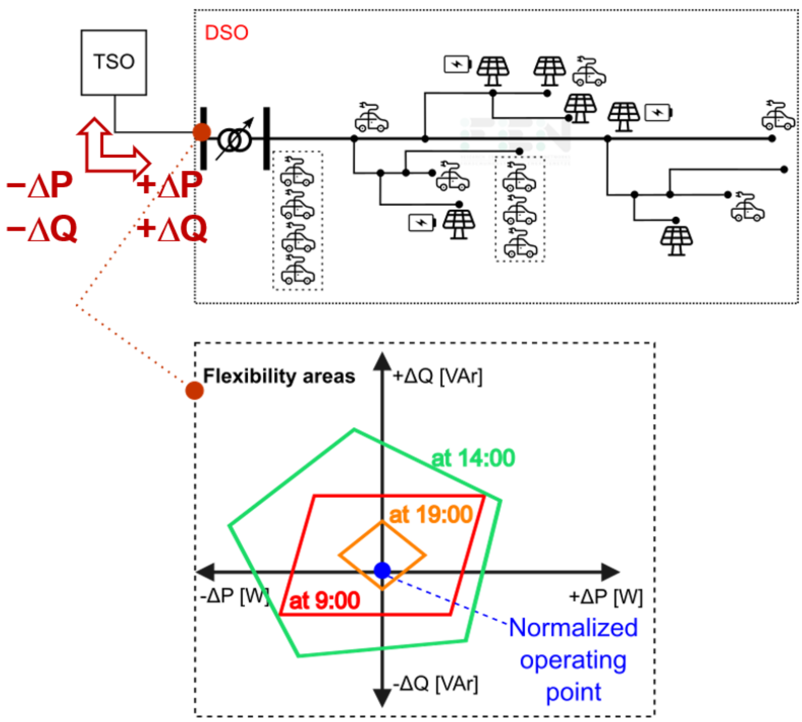


Figure 46 The concept of time-dependent flexibility area at the TSO-DSO substation

Assumptions in the analysis are as follows:

- The grid information (i.e., connectivity, line/transformer parameters, ratings) is known to be able to perform AC optimal power flow analysis.
- Expected amount of electricity generated by each solar PV as well as the electric demand are known by the utility/aggregator either day-ahead, or intraday in high resolution (e.g., every 15 or 60 minutes).
- The utility has the necessary DMS infrastructure to determine the operating point of the system day-ahead as well as intraday by using (i) the grid information, (ii) the information communicated from the customer-side, i.e., net demand (including excess generation due to not locally consumed electricity generated by the solar PVs), state of charge of BESS, availability of the EVs, status of EV charging, and status of HPs (iii) the forecasts of demand and local generation.
- The utility has necessary telemetry infrastructure to retrieve voltage and current measurement in high time-resolution from each node in the network including the TSO-DSO interface substation.
- The distributed generation resources (i.e., solar PV) are treated as zero-cost generators for optimal power flow (OPF) analysis.
- The conventional electric demand provides a fixed percentage of active and reactive power flexibility (e.g., 10% of the demand). That is, 10% of the demand at a given time instant can be ramped down or ramped up as shown in Figure 47. The flexibility participation can be time-dependent and provided as a signal. How the consumer provides this flexibility (whether curtailing/increasing the consumption of a device such as boiler or heat pump etc.) is not within the scope of this project. The electric demand is assumed to provide active and reactive flexibility.
- Electric demand is modelled as constant active and reactive power. Constant-impedance and constant-current models can be adopted if needed.

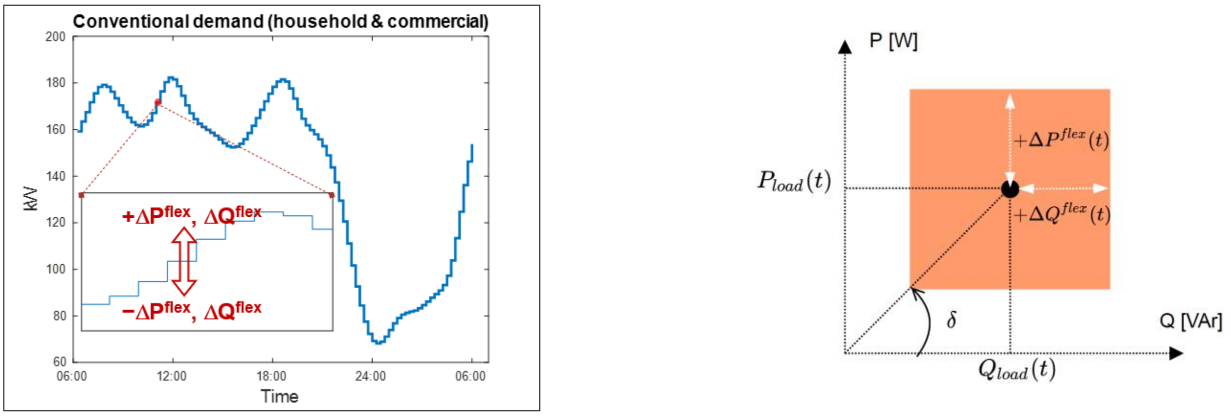


Figure 47 The flexibility provided by conventional electric demand (left), and the PQ flexibility capability curve (right).

Each solar PV owner provides a fixed percentage of flexibility out of available PV production (e.g., 10%). That is, 10% of the available solar PV generation at a given time instant can be curtailed. The flexibility participation can be time-dependent and provided as a signal.
The solar PV converters can provide reactive power capability (i.e., reactive power flexibility) with respect to a given PQ capability curve as shown in Figure 48. For illustration a V-curve is used, however, any other curve can be adopted.

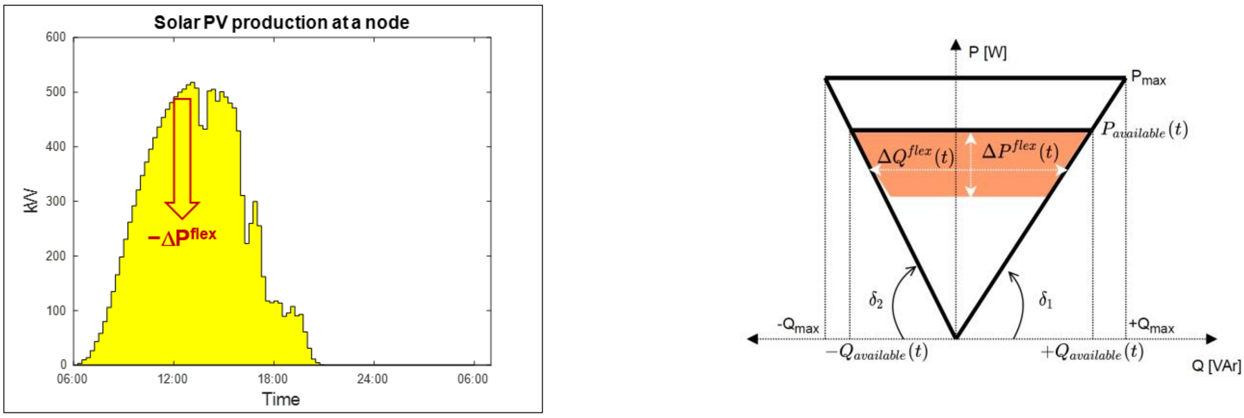


Figure 48 The flexibility provided by solar PVs (left), and the PQ flexibility capability curve (right).

The EV charging (active power) flexibility is by means of reducing/increasing the charging as shown in Figure 49. EV charging infrastructure at each site allows slow charging as well as continuous ramping down. The availability (the projection of the EV arrival and departure times) of each EV is known via a signal provided by the owner. Vehicle to grid is not allowed.

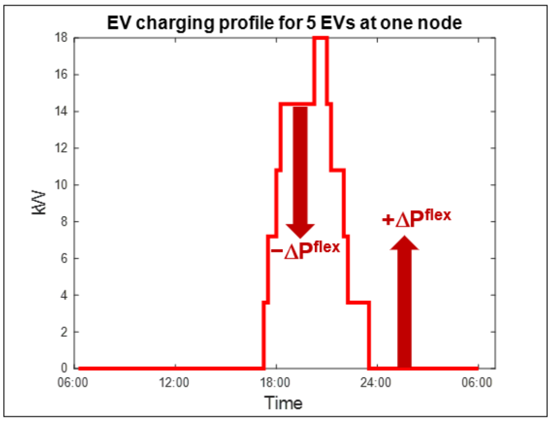


Figure 49 The flexibility provided by EV charging.

The electric heat pumps can provide (active power) flexibility by means of turning on/off as shown in Figure 50. Continuous ramping up/down is not allowed. The availability of HPs is known via a signal provided by the owner.

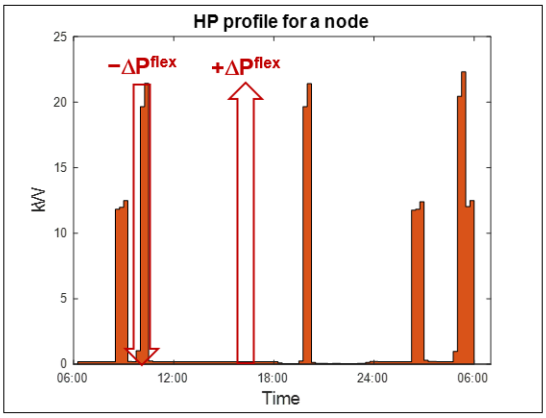


Figure 50 The flexibility provided by electric heat pumps

It is assumed that all BESS owners own PV but not all PVs are equipped with BESS. The BESS charging is driven by the excess energy produced by the solar PV. BESS charging schedule is assumed to start either at the time when there is excess solar, or at around the time when the projected maximum solar generation occurs. BESS can provide active and reactive power flexibility as shown in Figure 51.

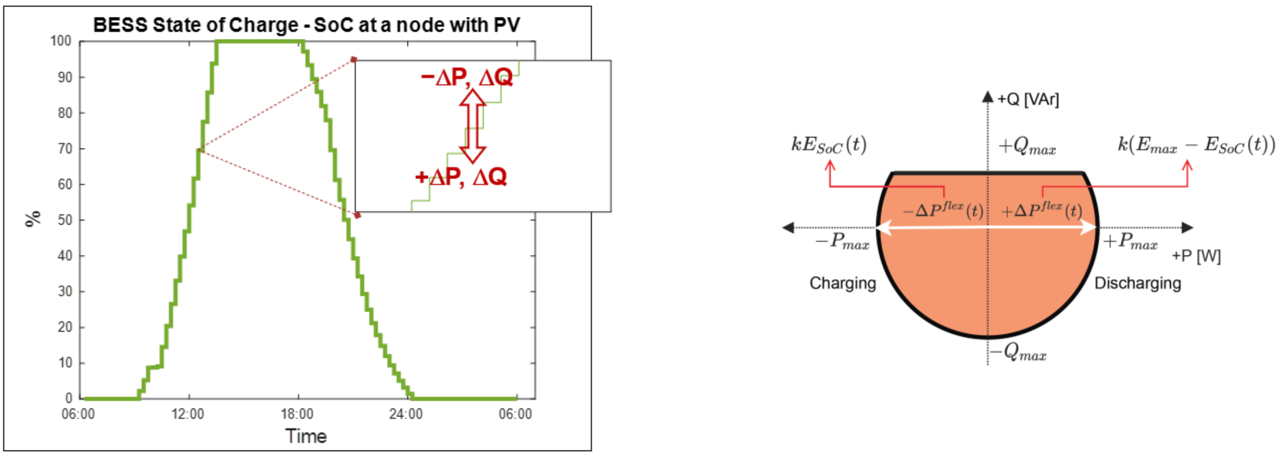


Figure 51 The flexibility provided by BESS (left), and the PQ flexibility capability curve (right).

Note that +ΔQ flexibility (discharging) is limited due to its dependence on the nodal voltage and the internal capacitor voltage.

The network is assumed to be structurally balanced (i.e., there are no 1-/2-phase feeders connected to a 3-phase feeder).
The electric demand is balanced at each phase, and, thus, positive-sequence modelling is used.

Our initial findings show that there is a potential to reduce the winter reserve requirements for hydro plants in Switzerland, thanks to the fact that the aggregated DER flexibility spread across the country relieves congestion resulting in cheaper electricity imported from the neighbouring countries.

We model the energy and reserve market of Switzerland, along with the energy market of its neighbours, such that energy and reserves are simultaneously dispatched. We model the active power flexibility of each "flexibility generator" at the TSO-DSO substation with its associated costs varying at every time instant. *Our initial findings* show that less upwards flexibility is provided by the hydro plants in Switzerland thanks to the flexibility provided by the DERs resulting in increased energy production by the cheap hydro plants, which finally reduces the overall dispatch costs.

The ways of procuring (*e.g., by means of bidding in a flexibility market*) and scheduling (*e.g., by means of performing a multi-period scheduling over a time horizon*) such flexibility is not within the scope of this project.

O. DiGriFlex Project

Project basic information

The objective of this research project is to develop effective forecasting and optimal control methods to ensure efficient and secure operation of distribution grids, as well as flexibility and ancillary service provision from local low voltage distribution grids to the upstream medium/high voltage grids, under uncertainties. The source of uncertainties varies from stochastic distributed power generation (e.g., solar and wind power generation) and demand uncertainties to system model uncertainties (e.g., uncertain parameters of overhead lines and cables). Secure operation deals with satisfaction of technical constraints of distribution grids such as nodal voltage limits, power flow limits of lines/cables, and technical constraints of grid connected resources such as distributed generation and battery storage capacity limits. Efficient and optimal operation deals with both technical and economic objectives of local distribution operators such as minimization of voltage deviations and line's losses, maximization of ancillary service provision to upstream medium and high voltage grids, and minimization of real-time imbalances with respect to predefined schedules. The secondary objective of the project is to implement the above forecasting and optimal control methods in a test case low voltage distribution grid and demonstrate the effectiveness of the developed methods for different grid operation scenarios.

List of partners: HEIG-VD/IESE (Institut d'Énergie et Systèmes Électriques), HEIA-FR, EPFL PWRS, University of Naples Federico II, University of Naples Parthenope, DEPsys SA

Source of funding: Swiss Federal Office of Energy (SFOE) through ERA-Net Smart Energy Systems Joint Call 2018

Duration: 2019 – 2021

Webpage: http://iese.heig-vd.ch/projets/digriflex

Project learnings

Context and key questions. In the context of energy transition, emerging local power distribution grids are characterized by; (a) high penetration of intermittent and variable distributed generation from Renewable Energy Sources (RES), (b) active consumers and flexible consumption, and (c) interconnection to the local communication and transportation systems. These impose the following challenges to the optimal operation and control of distribution grids:

- High stress on the low voltage distribution grids regarding bi-directional power flow that must be addressed, from both static and dynamic aspects.
- High level of uncertainties concerning the difficulties in the forecast and control of the power generation (caused by the stochastic nature of RES) as well as uncertainties in power consumption (e.g., caused by the stochastic profile of electric vehicle charging).

To address these challenges, it is necessary to improve the observability (by employing measurement devices and local data acquisition systems), and the controllability (by employing controllable resources, such as battery energy storage systems), of distribution grids. Moreover, efficient forecasting and optimal control methods are required to ensure that controllable resources are used in the most efficient way with respect to the state of the system. Note that the involved models/algorithms must be capable of; (a) analysing the huge amount of data coming from measurement devices and data acquisition systems, and (b) creating the control signals (for controllable resources) in very short time-steps, near real-time operation of the system.

This potential capability of low voltage distribution grids for controlling distributed flexible resources, makes them a suitable choice for provision of flexibility and ancillary services to the upstream medium and high voltage grids. In this respect, the main questions that this project addresses are:

1. How the flexible resources within distribution grids should be controlled to ensure secure operation of the grid in real time? What is the impact of uncertainties associated with the local generations and demands?
2. What are the potential flexibilities and ancillary services that distribution grids could provide to the upstream transmission grids? What are the technical constraints?
3. What is the optimal strategy/schedule for controlling flexible resources within a low voltage distribution grid? What is the efficient way to handle uncertainties in the development of the optimization problem?

Objectives. The first objective of this research project is to develop effective forecasting and optimal control methods to ensure efficient and secure operation of distribution grids, as well as flexibility and ancillary service provision from local low voltage distribution grids to the upstream medium/high voltage grids, under uncertainties. The source of uncertainties varies from stochastic distributed power generation (e.g., solar and wind power generation) and demand uncertainties to system model uncertainties (e.g., uncertain parameters of overhead lines and cables). Secure operation deals with satisfaction of technical constraints of distribution grids such as nodal voltage limits, power flow limits of lines/cables, and technical constraints of grid connected resources such as distributed generation and battery storage capacity limits. Efficient and optimal operation deals with both technical and economic objectives of local distribution operators such as minimization of voltage deviations and line's losses, maximization of ancillary service provision to upstream medium and high voltage grids, and minimization of real-time imbalances with respect to predefined schedules.

The second objective of the project is to implement the above forecasting and optimal control methods in a test case low voltage distribution grid and demonstrate the effectiveness of the developed methods for different grid operation scenarios.

Methodology and Outcomes

Techno-economic studies. The different groups of ancillary services (balancing, congestion management, voltage management and service continuity) have been evaluated. Depending on which service is considered and whether export or local use is considered, the relative value of the service is given by (i) the cost of the equivalent network reinforcement, (ii) the cost of a tap changer distribution transformer or (iii) the historical value of the corresponding service in the transmission grid. Items (ii) and (iii) are relatively straightforward: figures have been collected by considering the relevant historical costs. The novelty of the approach is however concentrated in item (i), the relative value of the network reinforcement avoided. An ex-ante average value of this relative value for flexibility has been determined by considering a large number of possible network reinforcements within two grid areas (rural and urban) and then computing an average cost of the reinforcement for each kWh that could be additionally injected into the system. The relative value of the flexibility is obtained by discounting the cost for the reinforcements in the entire grid area and computing an adequate average.

Forecasting systems. The methodologies developed for day-ahead and near real-time forecasting (i.e., 10 minutes ahead) of load and PV power are based on ensemble approaches, i.e., combination of individual forecasts coming from different underlying models. Methodologies are developed within a probabilistic framework in which predictive quantiles of the target variable for the target forecast horizon are generated by the forecasting system. Forecasts can be rescaled in order to extract just a single, spot value (deterministic framework), on occurrence (e.g., to be used as inputs of the real-time optimization models).
Several methodologies have been developed[83,84]:

- A Multivariate Quantile Regression (MQR) model based on underlying Quantile Regression Forest (QRFs)
- A Bayesian Bootstrap (BB) model based on underlying Linear Quantile Regression (LQR), Gradient Boosting Regression Tree (GBRT), and Quantile Regression Neural Network (QRNN) models
- A hierarchical GBRT/QRNN model, based on ranking and combination of NWPs
- A Derivative-Persistence (DP) model

The BB with LQR underlying model has been selected for the actual implementation

Two-level optimization system. The optimization system is developed based on a rolling horizon two-level optimization model. The first level deals with prescheduling of controllable resources in a day-ahead basis (DA), whereas the second level deals with near real-time scheduling (RT) of all the controllable resources. For DA optimization, two alternative methods, namely, "stochastic programming", and "Distributionally Robust Chance Constrained (DRCC) Programming" are developed, implemented and compared in terms of optimality, robustness, and scalability. The near-real-time optimization is developed based on a deterministic linear programming model.

Validation and demonstration. Both DA and RT optimization models are fed by the DA and RT forecasting system, then tested and validated in the ReIne[85] laboratory (a reconfigurable low voltage distribution grid testbed). Figure 54 shows the schematic of validation test in the ReIne environment. The data acquisition is developed based on the monitoring system of the ReIne distribution grid equipped with GridEye devices by DepSys.

[83] Bozorg, M., Bracale, A., Carpita, M., De Falco, P., Mottola, F. and Proto, D., 2021. "Bayesian bootstrapping in real-time probabilistic photovoltaic power forecasting." Solar Energy, 225, pp.577-590.
[84] M. Bozorg, A. Bracale, P. Caramia, G. Carpinelli, M. Carpita, P. De Falco, "Bayesian bootstrap quantile regression for probabilistic photovoltaic power forecasting," Journal of Protection and Control of Modern Power Systems, vol.5, 21, pp. 1-12, 2020.
[85] M. Carpita, J.-F. Affolter, M. Bozorg, D. Houmard, and S. Westerlin, "ReIne, a flexible laboratory for testing the low voltage networks", In proc. of the 21st European Conference on Power Electronics and Applications (EPE'19 ECCE Europe), September 2019.

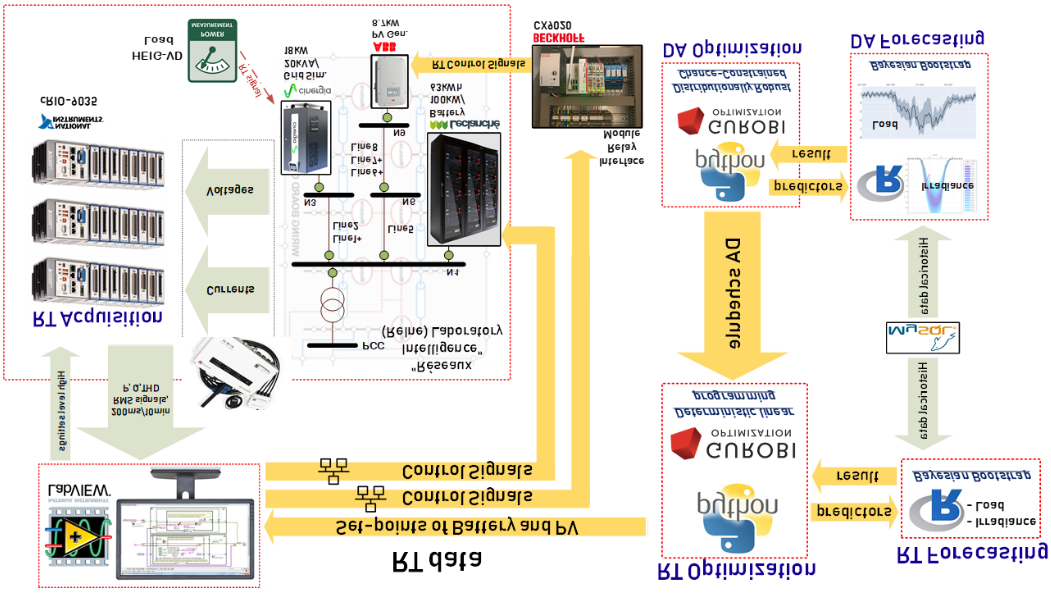


Figure 52 Implementation structure of validation test

P. ACSICON & SCCER-FURIES-Dynamics projects

<u>Project basic information</u>

The project investigates dynamic power system stability, which is a growing concern for both large transmission and distribution grids. The main challenges arise from reduced inertia as converter-based generation replaces traditional synchronous machines. Depending on the time of day and the load flow situation, large transmission grids already face several dynamic challenges, ranging from inter-area oscillations, temporary frequency violations, to system splits into multiple synchronous areas.

The two projects have investigated the potential of dynamic grid support from converters as well as the necessary practical considerations regarding controller tuning to allow penetration levels of grid- forming DERs upwards of 100% of the distribution grid load. At the moment, there is no industry consensus on what control structures should be used and how to tune and configure such controllers for maximum benefit to the overall stability of the grid. Furthermore, a large share of the converters will be installed at the distribution level where their effect on overall system stability is not well understood.

To provide a robust solution to these challenges, the projects (i) developed generic dynamic distribution grid models for transmission grid studies, (ii) deployed the models in a large-scale power system simulation of large transmission grid disturbances (including system splits) and (iii) identified the critical share of converters with and without grid-support to maintain power system performance at today's level.

List of partners: Research Centre for Energy Networks (ETH Zürich), Swissgrid, Hitachi-ABB Power Grids Research

Source of funding: Swiss Federal Office of Energy, Innosuisse, Swissgrid

Duration: 2017 - 2020

Webpage:
https://www.fen.ethz.ch/activities/system-operation/acsicon.html
https://www.fen.ethz.ch/activities/system-operation/sccer-furies-dynamics.html

<u>Project learnings</u>

Resilience using dynamic flexibility from converter-based generation

Resilience describes the capability of a system to recover from serious disruptive events back to normal operation. An important resilience aspect of the power grid is related to dynamic power system stability, as seen during a black-out in South-Australia (2016) or system separations of the ENTSO-E grid (2006, 2021). In recent projects we have studied the dynamic behavior and stability during large disturbances on all grid levels, with a particular focus on the challenges and potential from converter-connected renewable energy sources. The energy transition is expected to lead to an increased generation from converter-connected distributed energy resources (DER) like photovoltaic and wind. At the same time, some traditional synchronous machine-based generation is being decommissioned, leading to new dynamic stability challenges at both the transmission and distribution grid level, e.g., stronger frequency transients due to reduced inertia and voltage problems during transients with high local shares of converter-connected sources. Recent developments have resulted in so-called grid-forming converter control architectures that also enable the provision of grid services such as frequency and voltage support through adequate responses in terms of active and reactive power injections, for which grid operation has traditionally relied on synchronous machine- based generation.

Since most converters will be installed at the distribution grid level, the corresponding stability challenge and support functionality is the combined result of thousands individual units. A detailed dynamic modeling of all underlying distribution grids in a transmission grid is not possible both for data and complexity reasons. To derive an aggregated dynamic distribution grid model, the CIGRE medium voltage system (Figure 53) is used as benchmark. The different DER-units are equipped either with a grid-following (current-control) or grid-forming (Virtual Synchronous Machine) architecture, linearized, and aggregated using model reduction techniques. The resulting models can be used with varying DER-penetration levels for simulation-based investigations of dynamic stability and resilience.

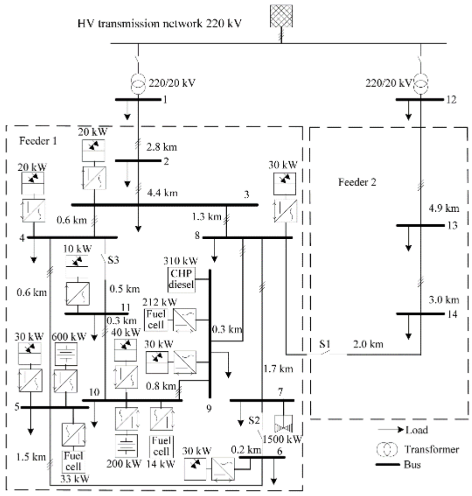


Figure 53 Cigre MV system used for stability studies with different penetration levels of grid-forming converters. At the transmission grid level, the system can be modeled in an aggregate manner.[86]

[86] [Source: Kai Strunz (Convener). Benchmark systems for network integration of renewable and distributed energy resources. Tech. Report 575, CIGRE, 2013)]

Key findings on resilience from dynamic converter control:

The dynamic flexibility of converter-based DER has the potential to overcome the challenges caused by the replacement of conventional synchronous machines and to maintain or even improve the overall system resilience.

The following use cases have been found to show a high benefit for system resilience from dynamic converter support during severe disturbances:

1. *System support during faults near the distribution grid feeder:*

Grid-forming converters can react to such disturbances and the subsequent voltage drop by injecting reactive power to uphold the voltage level in the distribution grid and improve the recovery from the fault. Figure 2 (left) depicts the aggregated reactive power response of the Cigre benchmark system during a voltage step for increasing shares of grid-forming converters.

2. *Support of distribution grid disconnections (islanding):*

During this disturbance, a black-out can be prevented if the distribution grid can temporarily rely on local production units. Figure 2 (right) shows the grid-forming converter's aggregated active power response during a temporary islanding of the Cigre benchmark system, allowing a continuous supply of the system loads. Note that the converter also generates the system frequency and perform a seamless reconnection to the transmission grid, after the disturbance has passed (not depicted here).

3. *Support during a transmission system split:*

This is one of the most severe issues at the transmission grid level, short of a black-out, where the grid separates into multiple synchronous areas. Figure 56 depicts such a system split that has occurred in 2006 and is now studied with different supply and control configurations. The converters additional active power injections reduce the frequency nadir and prevent subsequent generator trips and cascaded outages. Investigation over a broad range of scenarios and load distributions confirm, that equipping a small share of the new converters (5%-10%) with grid support capabilities is sufficient to maintain the dynamic power system performance at today's level, even if more than 50% of the synchronous generation is otherwise replaced by converters without grid support.

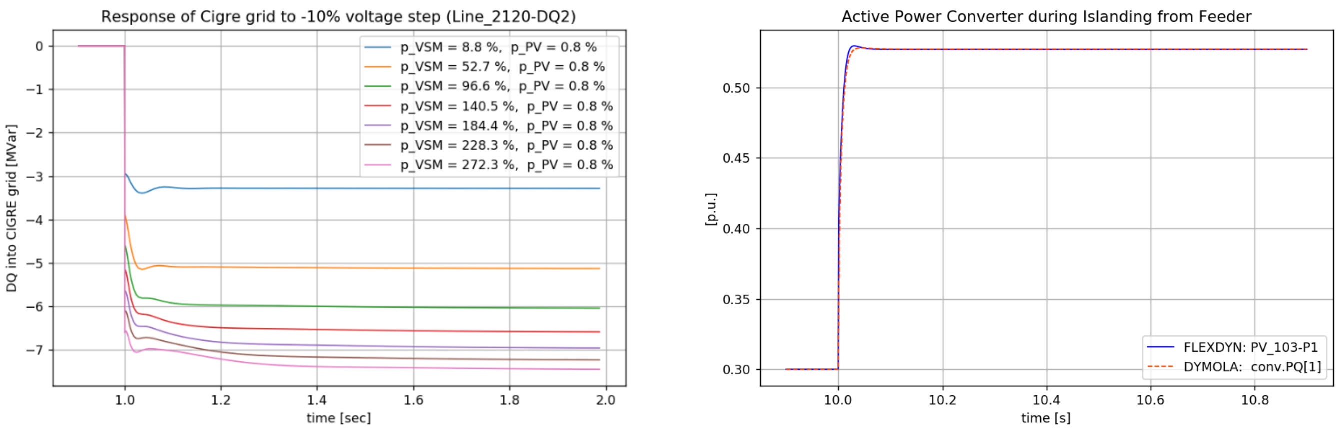


Figure 54 Transmission system split

(Left: Reactive power response of the Cigre benchmark system during a fault near the feeder with subsequent voltage drop, for increasing shares of grid-forming converters. Additional reactive power injection of the converters supports the voltage level. Right: Active power response during a temporary islanding situation. The grid-forming converters enable continuous supply of the loads by temporarily injecting additional active power and supporting a reconnection to the transmission grid after the disturbance. *[Source: own simulations and illustration])*

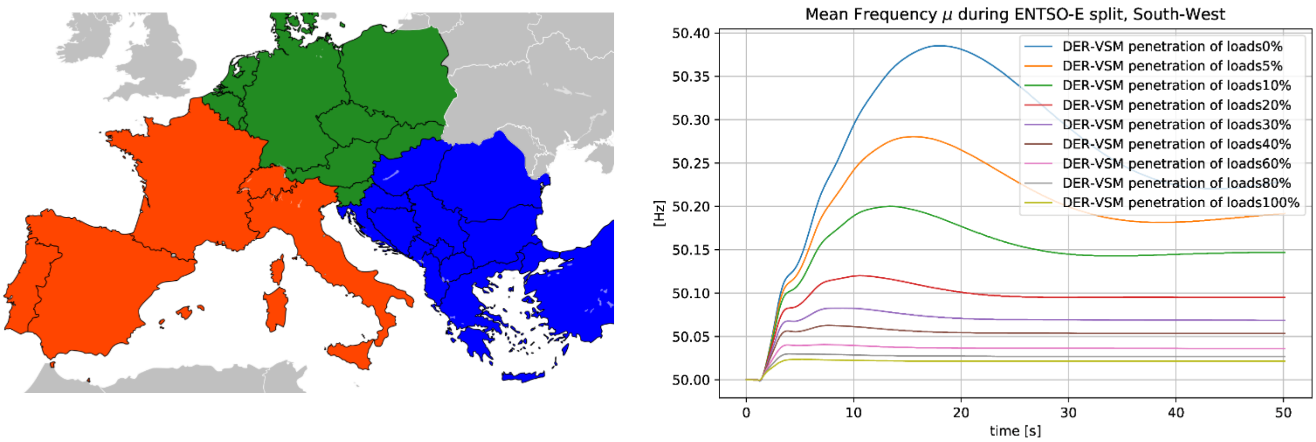


Figure 55 Transmission system split 2 (Left: ENTSO-E transmission grid during as system split into 3 synchronous areas. Right: Frequency transient of the South-West region for increasing shares of grid-forming converters. The converters additional active power injections reduce the frequency nadir and prevent subsequent generator trips and cascaded outages. *[Source: own simulations and illustration])*

Related projects:

ACSICON: Novel Analysis and Control Solutions for Dynamic Security Issues in the Future ENTSO-E Network with High Converter-Based Generation, https://www.aramis.admin.ch/Dokument.aspx?DocumentID=67536

SCCER-FURIES: Critical large-scale disturbances of the future ENTSO-E system https://www.fen.ethz.ch/activities/system-operation/sccer-furies-dynamics.html

Q. HONOR Project

Project basic information

Main goal: The HONOR (Holistic flexibility market integration of cross-sectoral energy sources) project aims at development and evaluation of a trans-regional flexibility market mechanism, integrating cross-sectoral energy flexibility at a community-wide level. The specific developments include a market mechanism for grid flexibility, industrial grade supervision solutions, data-driven state monitoring applications and cyber-security assessments. The project also investigates the integration of distributed small-scale assets through aggregators into the flexibility market that currently do not have access to any markets.

List of partners: The project consortium comprises project participants from Denmark, Sweden, and Norway, which include: TU Dortmund, SWW Wunsiedel, Danish Energy, Norwegian University of Science and Technology, Foreseeti AB, Kungliga Tekniska högskolan, Technical University of Denmark, PSI Software AG

Source of funding: The project funding is in the framework of the joint programming initiative ERA-Net Smart Energy Systems, with support from the European Union's Horizon 2020 research and innovation program ERA-NET cofounded project.

Duration: 2019-2022

Webpage: https://honor-project.eu/

Project learnings

Flexibility offered from the demand side and across energy sectors in a smart energy system can be a valuable asset for the management of electricity networks and facilitate energy efficiency through increasing electrification and extended hosting capacity for distributed renewable power generation. To address flexibility trading, HONOR will assess a new electricity market mechanisms to determine the optimal operation of flexible resources and their allocation to either power market, grid balancing, or local grid bottlenecks, improving welfare distribution among stakeholders. The flexibility introduced by HONOR has the ability to change market operation results, including the market-clearing price and the values of the energy and ancillary services transacted by the market participants. The flexibility market mechanism will serve operators to procure predefined services in a coordinated, fair and efficient manner, as DSOs and TSOs will explicitly take physical decentralized grid effects on distribution and transmission levels into consideration.

A key impact of the HONOR project will be the integrated demonstration of all fundamental steps of the local cross-sectoral flexibility coupling: matching flexibility needs & modeling availability, bidding, reserve activation and verification. Including all steps of the process in a field demonstration creates a credible precedent for further market development. In particular, local combined heat and power (CHP) generation is receiving large investments as a means to reduce greenhouse gas emissions and improve energy efficiency. By integration of such district heating resources into optimal operation of the electricity distribution system, societal welfare is increased, and the value is generated locally.

Objectives of the project

The active management of distribution grid level flexibility poses challenges, not only because of conflicting operational objectives between local and regional utilization, but also due to the lack of adequate operational decision support tools at the hands of grid operators. Developing local business opportunities and solving technical challenges that can be replicated in an European context, will require innovative ICT-based solutions and develop an awareness of new vulnerabilities, risks and mitigation strategies. The project aims at both deployment and assessment of a replicable flexibility approach, that enables

- Coupling energy, supply and traffic sectors at a community level,
- Exchange of grid flexibility locally as well as beyond the local region,
- Non-discriminatory participation from any type of flexibility resource
- Supervision, monitoring and verification of flexibility services with minimal business and technical overhead,
- Online and ex-post validation of grid and resource operations,
- Replicability of concepts and solutions in an European-wide context and
- Routine cyber-security assessment through nominal architectural models.

Concretely, these requirements will be met by achieving the following objectives:

1. Demonstrate the combined business and operational chain of cross-sectoral coupling and operation of flexibility market and dispatch with local community stakeholders
2. Validate the full technical solution in a relevant transnational environment, employing state-of-the-art experimental techniques,
3. Assimilate experience from partners and anchor project results by means of workshops with expert end-users (Germany and Denmark) to ensure relevance of the project developments in the local context,
4. Mature existing market platforms for local flexibility services and develop further the concept of a regional and transregional exchange,
5. Develop industrial-grade interoperable decision support, supervision and collaboration platforms and state-of-the-art dispatch and control solutions,
6. Development of innovative data-driven monitoring, detection and verification solutions for the supervision of the flexibility market operation and ICT infrastructure,
7. Development and application of Cyber-security assessment models for the complete trading and operational ICT infrastructure,
8. Provide an overall economic evaluation and risk assessment accounting for market development opportunities and cost of cyber vulnerabilities

Business layer for flexibility market. The first step towards creating a holistic framework covers the definition of required business roles and their relations. The results are visualized in Figure 56 through a business layer according to the Smart Grid Architecture Model (SGAM). Depending on the given responsibilities, multiple roles can be occupied by single actors.

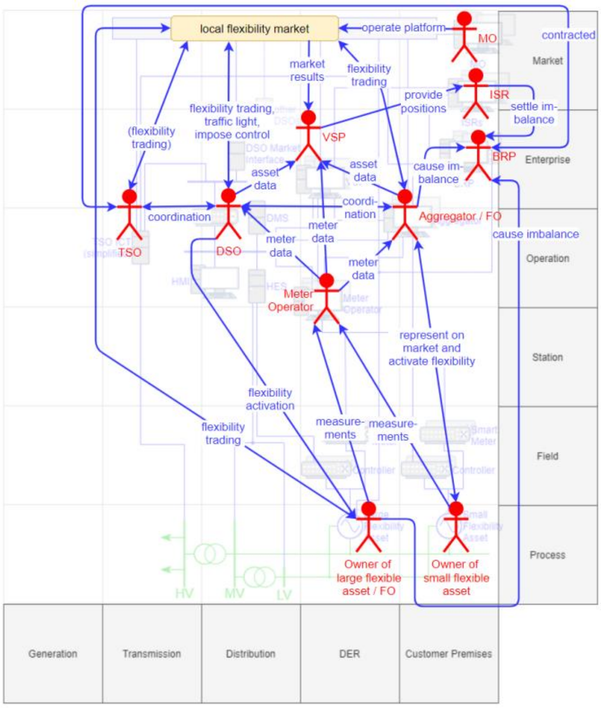


Figure 56 Business Layer within System Architecture

The business layer in Figure 56 elaborates the relation between participating parties. The owner of the small flexible assets fully transfers the marketing and control of his flexibility to the aggregator, who therefore occupies the role of the Flexibility Operator (FO). By doing this, the owner has the ability to include his flexibility into a pool of assets, which can be sold on platforms in order to make a profit for the owner, while the aggregator collects his share of the revenue as well. The exact definition for the aggregator depends on the market design and the integration into the general market system, as a participation in other markets, like it is done through a virtual power plant today, could be possible as well. The owner of a large flexible asset markets the flexibility themselves and the activation can be done internally, or by the Distribution System Operator (DSO) in case of large Distributed energy resource (DER) units with an existing communication, depending on the asset type. Both types of FO are contracted to a Balance Responsible Party (BRP), who is contracted with the Transmission System Operator (TSO) through the Balance Group (BG) in the control area, and the FO flexibility trading causes imbalances for the BRP. In HONOR this is dealt by committing the BRP to balance the imbalances caused by the FOs on the intraday market or through internal mechanisms. The meter operator collects measurements from the flexibility owners and provides the data to the aggregator, the DSO, and the Verification Service Provider (VSP). Depending on a country's regulations, the metering can be part of the DSO. The DSO co-manages the market platform and purchases flexibility, if necessary, or closes the market to impose control in critical situations. The coordination between TSO and DSO is an important part of the local flexibility market. While this depends on the market design, some core components of that connection can be specified. Local markets aim at congestion management, which will primarily be relevant in the transmission system, though the units are positioned in the distribution system. A flexibility demand by the TSO has to be feasible within the grid capacities of the distribution system. Therefore, this demand has to be realized through a market interaction by the DSO, based on the TSOs incentives. Thus, a close coordination between DSO and TSO is required for the efficient operation of the flexibility markets. The VSP has to ensure that the contracted flexibility is physically delivered. Therefore, the market results have to be made available to the VSP by the MO. Furthermore, the VSP uses meter data and additional asset data from the aggregator and DSO (asset location, asset type, BRP contracting) to verify the market transactions. The VSP forwards that to the ISR, who performs the monetised settlement and ascribes the results to the BRP. If a FO does not deliver the contracted flexibility, the VSP detects this and initiates the handling according to the market framework, which could result in penalty payments, a reduction of the reliability score or a temporal exclusion from market transactions for the FO.

R. CINELDI

Project basic information

Main goal: CINELDI is one of the Centres for Environmental-Friendly Energy Research in Norway.
FME CINELDI - The scheme of the Centres for Environment-friendly Energy Research (FME) seeks to develop expertise and promote innovation through focus on long-term research in selected areas of environment-friendly energy. There are today 10 centres within renewable energy, energy efficiency, social sciences and CO2-management. The research activity is carried out in close cooperation between prominent research communities and users. The centres will operate for eight years.

List of partners: 30 partners in total, where research partners are SINTEF and NTNU.

Source of funding: 365MNOK from Research Council of Norway

Duration: 2016-2024

Webpage: https://www.sintef.no/projectweb/cineldi/

Project learnings: CINELDI enables a cost-efficient realisation of the future flexible and robust electricity distribution system by developing new concepts, technologies and solutions. By providing new visionary smart grid-solutions and testing them in laboratory and real-life environments, the knowledge and experience gained helps grid companies, the system operator, manufacturers and ICT companies to develop and integrate new technologies and work processes, stimulating innovations.

These innovations will in turn contribute to a more sustainable energy system by increasing influx of renewables, electrification of transport and more efficient energy use. To achieve this, the digitalisation of the distribution system is needed.

Long-term research is needed in order to digitalise the electricity grid and make the necessary transformation of the grid for the future. This will pave the ground for increased distributed generation from renewable resources, electrification of transport, and more efficient energy use.

Introducing variable distributed generation (DG) will increase the need for flexibility in the grid. The development of a flexible energy system is crucial to realise energy and climate targets and to ensure security of supply in Norway and Europe. To obtain this, flexibility on the distribution level such as battery banks, generation units and dispatchable loads are crucial. Several projects, studies and pilot are focused on these opportunities.

For more, please visit: https://www.sintef.no/projectweb/cineldi/pilot-projects-in-cineldi/flexibility-applied-on-system-services/

S. Holistic LINK solution

Main goal: Finding the Smart Grid paradigm and a new architecture to enhance the controllability associated with future power system operation

List of partners: TU Wien, Austria

Source of funding: TU Wien, Austria

Duration: Start: 02.01.2014 End: 31.12.2018

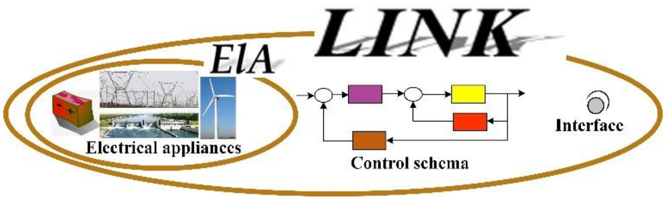
Webpage: https://www.powersys-link.com/

Project learnings

LINK paradigm, derived from the fractal signature of smart grids, consists of unique and independent elements. It enables the massive integration of distributed energy resources by solving technical problems in a decentralized manner, reducing the need for extremely ramified and complex central coordination, and thus facilitating the realization of smart grids. It enables the Sector Coupling[87] and Energy Communities[88].
Operational flexibility is the main feature of the holistic LINK solution, defined by design since the holistic model phase.

Architectural Paradigm LINK and the associated holistic model

The essential requirement of the architectural paradigm for unique and independent elements is fulfilled by using the smart grids' fractal pattern ElA as one of the fundamental elements of the paradigm[89]. The ElA fractal pattern is combined with control schemes and interfaces to create the architectural paradigm of Smart Grids.
The architectural LINK-Paradigm is a set of one or more ElAs, i.e., a grid part, storage device, or producer device, the controlling schema, and the interface.



[87] ETIP SNET Position Paper, *Smart Sector Integration, towards an EU System of Systems*, July 2020
[88] INTERACT – Integration of Innovative Technologies of Positive Energy Districts into a Holistic Architecture, https://www.ped-interact.eu/

[89] Ilo A (2019) *Design of the Smart Grid Architecture According to Fractal Principles and the Basics of Corresponding Market Structure*. Energies, vol 12, p 4153. doi:10.3390/en12214153

LINK-Paradigm facilitates modelling of the entire power system from high to low voltage levels, including CPs. It includes the description of all power system operation processes such as load-generation balance, voltage assessment, dynamic security, price and emergency driven demand response, etc.90. The LINK-Paradigm is fundamental to the holistic, technical, and market-related Smart Grid model with large DER shares. The figure below shows the holistic technical model (the "Energy Supply Chain Net"). It illustrates the links' compositions and their relative position in space, both horizontally and vertically. In the horizontal axis, the interconnected High Voltage Grids (HVG) are arranged. They are owned and operated by Transmission System Operators (TSO). Medium (MVG) and Low Voltage Grids (LVG) and the Customer Plant Grids (CPG), including the HVG to which the MVG is connected, are set vertically. MVGs and LVGs are owned and operated by the DSOs, while customers use CPs.

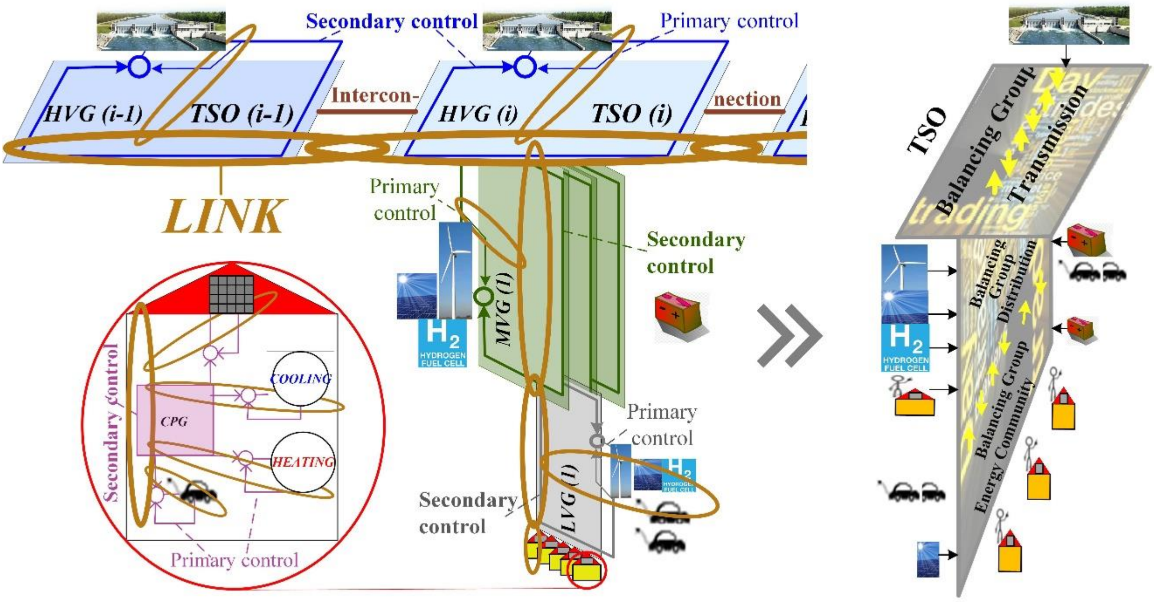


Figure 57 Overview of the holistic models: (a) Zoom in CP; (b) Technical model the "Energy supply chain net"; (c) Market model.

The "Energy Supply Chain Net" model is a set of automated power grids intended for chain links (abbreviated as links), which fit into one another to establish a flexible and reliable electrical connection. Each link or link bundle operates autonomously and has contractual arrangements with other relevant boundary links or link bundles[91].

It illustrates the links' compositions and their relative position in space, both horizontally and vertically. In the horizontal axis, the interconnected High Voltage Grids (HVG) are arranged. They are owned and operated by Transmission System Operators (TSO). Medium (MVG) and Low Voltage Grids (LVG) and the Customer Plant Grids (CPG), including the HVG to which the MVG is connected, are set vertically. MVGs and LVGs are owned and operated by the DSOs, while customers use CPs. The figure shows an enlarged view of the customer plants according to the holistic LINK model.

The holistic model associated with the energy market is derived from the holistic technical model, the "Energy Supply Chain Net". The whole energy market consists of coupled market areas (balancing groups) at the horizontal and vertical axes. TSOs operate on the horizontal axis of the holistic market model, while DSOs operate on the vertical. Based on this model, TSOs and DSOs will communicate directly with the whole market to ensure a congestion-free distribution grid operation and take over the task of load-production balance. The owner of the distributed energy resources as well as the prosumers (producers and consumers of electricity) may participate directly in the market or may do so via Energy Communities (ECs)92. The Local Retail Markets creation attracts the Demand Response bids and stimulates investment in the Energy Communities areas.

Operational flexibility in LINK-solution

Grid-Link is one of the three elements of the LINK architecture that contains a grid part, secondary control and interface93 . LINK identified and considered the grid part, which exists within the customer plants, from the meters up to the sockets for the first time. This discovery enabled the standardization of structures across the power systems, including the customer plants, as shown in the following figure. Grid-Links are setup on high, medium, and low voltage levels and in customer plant level. The corresponding secondary controls for the pair frequency and active power (Hz/Watt) are shown in red. Since frequency is a global parameter of power systems, the sub-process load-

[90] Vaahedi E (2014) Practical power system operation. John Wiley & Sons, New Jersey

[91] Ilo A (2013) The Energy Supply Chain Net. Energy Power Engineering, vol 5, pp 384–390. **doi**:10.4236/epe.2013.55040

[92] Ilo A, Prata R, Iliceto A, Strbac G (2019) Embedding of Energy Communities in the Unified *LINK*-Based Holistic Architecture. CIRED, Madrid, 3-6 June, pp 1–5

[93] Ilo A (2022) Architecture in Ilo A and Schultis DL Holistic Solution for Smart Grids based on *LINK*– Paradigm. Springer ISBN: 978-3-030-81529-5.

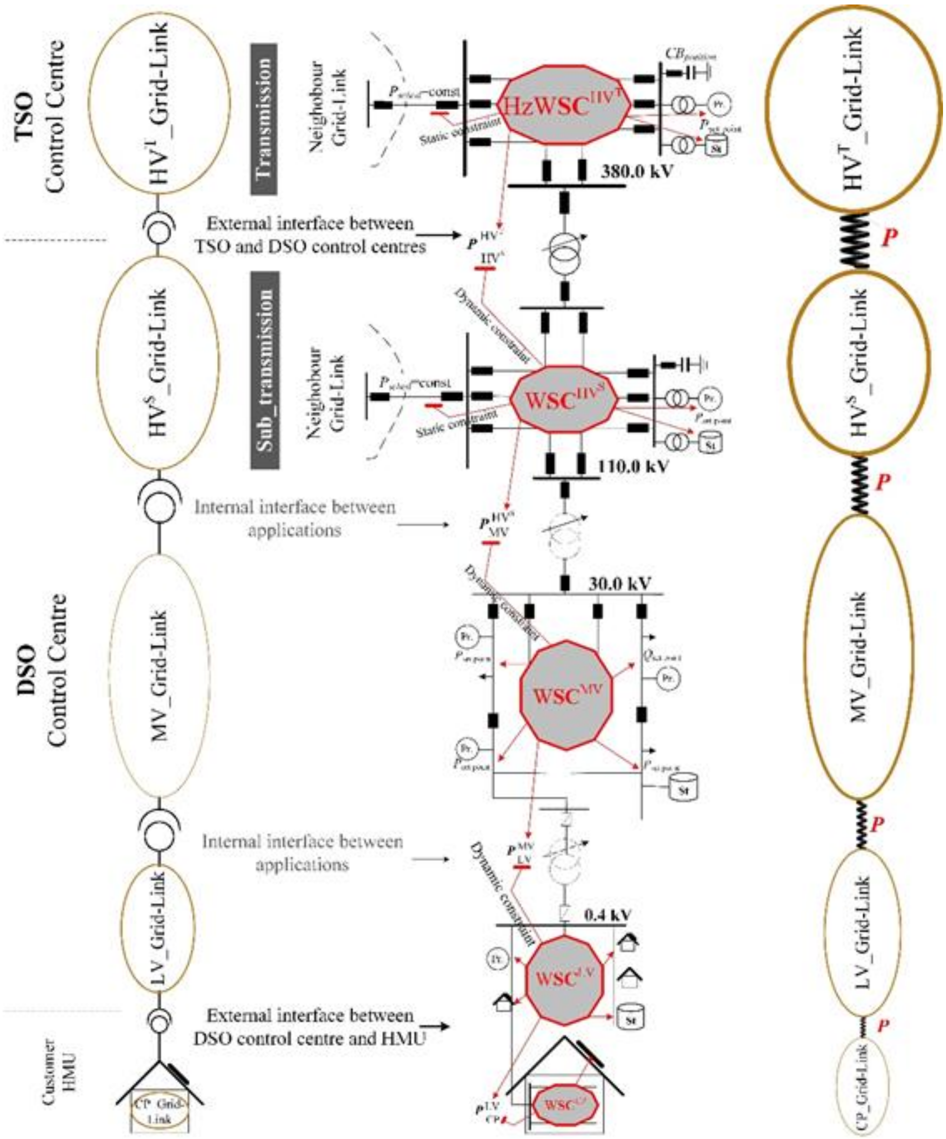
frequency control that happens minute-to-minute is attributed only to HVT_Grid-Links (set up on today's transmission grids). is stipulated for this Grid-Link. Meanwhile, both sub-processes, the operation planning and economic dispatch apply in all Grid-Links. Consequently, the load-generation balance process in Grid-Links in distribution and customer plant levels includes only the operation planning and economic dispatch sub-processes.

In the LINK-Solution, the load-generation balance process takes place in every Grid-Link or Grid-Link bundle. Every Grid-Link operator (TSO, DSO, or customer) conducts the load-generation balancing process in its Grid-Link or Grid-Link bundle. The load represents the summation of the scheduled exchanges to neighbouring external Grid-Links.
The chain of secondary controls (links) is used as an instrument to realise the operational flexibility from both sides, generation and demand. Following secondary control loops are set up:
Each of them calculates the relevant set points by optimising its own decisions that are subject to:
Its constraints; and

$$HzW\boldsymbol{SC}^{HV^T}, W\boldsymbol{SC}^{HV^S}, W\boldsymbol{SC}^{MV}, W\boldsymbol{SC}^{LV}, and\ W\boldsymbol{SC}^{CP}$$

Dynamic constraints imposed by neighbouring Grid-Links.

Dynamic constraints control the active power flow in a HzWSC chain. They change or should be recalculated in real-time, depending on the current situation. For example: if the active power supplied from HVS_Grid-Link into the MV_Grid-Link should be reduced by 20%, a new desired constraint is sent to the MV_Grid-Link. WSCMV recalculates the set points in its area by respecting the new condition with the superordinate grid. Otherwise, if the actual is not optimal for the MV_Grid-Link operation, a request is sent to the HVS_Grid-Link to change it, and so on. The same schema works across the entire HzWSC chain. This permanent exchange of desired active power P between different HzWSC loops creates a resilient interaction between them.



T. Indian best practices

Indian Power System is one of the largest synchronized interconnection in the world with a peak demand of approx 190 GW. India is a unique country in terms of topography and climatology due to which severe weather-based events are regularly experienced by Indian power system. On an average, Indian power system observes more than one High Impact Low Frequency (HILF) events every year which have potential to endanger reliability of Indian power system. The HILF events in India include Tropical Cyclones, Earthquakes, Landslides, Localised Wind Squall, Flood, Cloud burst, Silt (causing sudden closure of large hydropower complexes) etc. India has experienced major cyclones (Amphan, Fani, Phailin, Hud Hud, Vardah, Ockhi and Titli), several devastating floods (Including Uttarakhand and Kerala) and major earthquakes (including 7.7 intensity Nepal Earthquake). There have been events involving floods in major cities like Mumbai, Chennai, Vadodara etc. These events were potential threat to the power system operation right from generation to utilization of electricity through transmission and distribution. In addition to these, the localized thunderstorms had also been observed on a several occasions causing long outage of transmission lines on account of transmission- tower collapse or failure of transmission elements.

India regularly experiences cyclones of varying intensity on its eastern and western coast, the list of major cyclones which had potential to impact power system is given in the table below.

Super Cyclonic Storm Amphan formed in the Bay of Bengal in mid-May 2020 was one of the severe cyclone. It made landfall across West Bengal-Bangladesh coasts between Digha (West Bengal) and Hatiya Islands (Bangladesh) on May 20, 2020. It was the first super cyclonic storm on the tropical cyclone intensity scale of Indian Meteorological Department (IMD) in the Bay of Bengal since the 1999 Odisha cyclone.

Table 13 Cyclones impact on Indian grid (2013-2020)

No.	Name of Cyclone	Date	Impact	
			Demand Reduction	Grid element tripping
1	Phailin	12th Oct 2013	15000 MW (All India, Cumulative effect of cyclone and Festival)	Transmission Line tripping: 9 nos of 400 kV, 27 no of 220 kV, 37 no of 132 kV; Traction station effected: 3; Tower collapse-83 (220 kV & 132 kV),
2	Hudhud	11th Oct 2014	7000 MW (All India)	Transmission Line tripping: 28 no of 400 kV, 37 no of 220 kV and 85 no of 132 kV; Traction station effected: 12
3	Vardah	12th Dec 2016	1300 MW (All India)	Transmission Line tripping: 14 no of 400 kV and 19 no of 230 kV; Generating Unit tripping: 9 (2430 MW Gen loss), Traction station effected: 4; Tower collapse: 33 (230 kV),
4	Ockhi	30th Nov – 06 Dec 2017	2500 MW (Southern region) 7900 MW (Western Region)	Transmission Line tripping: 3 no of 220 kV, mainly 110 kV system and distribution system was affected
5	Titli	10th Oct 2018	3000 MW (All India)	Transmission Line tripping: 2 no of 765 kV, 4 nos of 400 kV, 6 no of220 kV, 8 no of 132 kV; Substation Dead: One 220 kV and One 765 kV substation became dead
6	Fani	3rd May 2019	3500 MW (Odisha, West Bengal)	Transmission Line tripping: 20 no. of lines tripped at 220 kV level and above Substation affected: More than 30 no. at 132 kv and above
7	Amphan	20th May 2020	8000 MW (Eastern Region)	Transmission Line affected: 14 no. of lines at 220 kV level and above opened on high voltage, 31 no. of lines tripped at 132 kV level and above Substation affected: More than 30 no. at 132 kv and above
8	Nisarga	3rd Jun 2020	Western Region	Transmission Line affected: 10 no. of lines at 220 kV level and above Substation affected: 2 no. at 220 kV and above
9	Nivar	25th Nov 2020	3000 MW (Southern Region)	Transmission Line affected: 96 no. of lines at 110 kV level and above Substation affected: 1 no. at 220 kV and above
10	Burevi	4th Dec 2020	2000 MW (Southern Region)	Transmission Line affected: 9 no. of lines at 110 kV level and above Substation affected: Nil

The steps taken in Indian power system operation in response to this event in different time scales are given below:

i. A web-based portal named *Weather Information Portal for Indian Power System* was used to obtain forecast of cyclone and its trajectory. It helped in taking preparatory actions for power system by providing estimated path of cyclone along with speed and timings at different coordinates.

ii. The cone of uncertainty was identified and all the power system elements falling in that geographical area were listed. Based on this information, a detailed action plan comprising of assessment of important parameters like forecast of demand reduction, threats to security margin, voltage control measures, Emergency Restoration System (ERS) and spare part availability, healthiness of protection and defence mechanism schemes, manpower and resource mobilisation, black start units, fuel reserve and battery healthiness for auxiliary supply, Back-up control centre, communication healthiness etc. was prepared.

iii. Amphan cyclone made its landfall in West Bengal's Sagar island on 19th May 2020. Due to rains and thunderstorms, less demand was observed in affected states, total twelve units with cumulative capacity of 3,440 MW were taken under reserve shutdown (RSD) during May 19 and 20, 2020. Less demand was accompanied with less flows on transmission lines and high voltages. To avoid high
iv. voltage, all available reactors were switched on and, in total fourteen lightly loaded transmission lines were opened at
v. voltage level of 220 kV and above.
vi. The availability of telemetry at control centres was ensured which helped in providing situational awareness to the operators in control room. The high-resolution data using WAMS (Wide Area Measurement Systems) provided timely information and helped in assessment of the situation.
vii. One major takeaway in real time operation from power system operation during Amphan cyclone was the importance of coordination and timely communication between different utilities. The web-based/Telephonic conferences between different utilities helped in drafting a strong action plan for possible contingencies. The timely sharing of information like manpower mobilisation and ERS availability helped in early restoration.
viii. Based on the management of each such event, several lessons are learnt which are tried for incorporation in planning. The system operator has been documenting the lessons learnt and future actions for each extreme weather-based event. The following points have been recommended which may require investments:
ix. The reliable and redundant telemetry at control centers is very important as uninterrupted good quality data is of paramount importance. The customized displays and additional screens for monitoring parameters based on SCADA and WAMS need to be identified for managing such unforeseen events in real time.
x. Design and strengthening of transmission towers to sustain high wind speed have been recommended to ensure their resiliency. Further, Transmission lines near to flood-prone areas have been recommended for pile type foundation to avoid any collapse.
xi. Plinth of substations situated in flood-prone areas are recommended to be made at a considerable height. Further, provision should also be made for direct jumper arrangement of incoming and outgoing transmission lines bypassing such substations, to avoid loss of lines in case of outage of substation.
xii. It has been recommended to all the utilities for maintaining adequate reserves of spare equipment to tackle emergencies based on the experience of such events.
xiii. Diesel Generator set for important infrastructure like substation/control center/generating station with adequate fuel storage has been recommended, so that continuity of auxiliary supply is ensured in case of unforeseen eventuality.
xiv. For Major cities, Ring main system has been recommended to reduce the outages due to tripping of trunk transmission lines. In cyclone-prone areas, underground distribution systems have been recommended for reducing the damage.
xv. The islanding schemes have been suggested for major load centers such that load-generation balance is inherent in them and in case of islanding, island remains self-reliant.
xvi. Periodic drills are being conducted to test the back-up control centers in case there is disruption of services at main control center.
xvii. Inter-utility coordination is being continuously worked upon, the web-based workshops are organized regularly for knowledge sharing among control centers at various levels.
xviii. The field testing of black start sources is regularly carried out to enhance the restoration procedure.

U. Existing European Framework

The EU energy policy recognizes the relevance of the use of flexibility for system operation. Flexibility related regulation is the following:

- Regulation (EU) 2019/943 on the internal market for electricity,
- Directive (EU) 2019/944 on common rules for the internal market for electricity,
- Regulation (EU) 2017/1485 establishing a guideline on electricity transmission system operation,
- Regulation (EU) 2015/1222 establishing a guideline on capacity allocation and congestion management,
- Regulation (EU) 2017/2195 establishing a guideline on electricity balancing,
- Regulation (EU) 2016/631 establishing a network code on requirements for grid connection of generators,
- Regulation (EU) 2016/1388 establishing a Network Code on Demand Connection is considered advantageous,
- Decision (EU) 2020/1479 of 14 October 2020 establishing priority lists for the development of network codes and guidelines for electricity for the period from 2020 to 2023 and for gas in 2020.

These existing network codes (NC) include several options to use flexibility with the purpose of guaranteeing the security of the systems. At the same time, the Clean Energy Package introduces some new high level guiding principles such as the Regulation and Directive on the internal market for electricity, both approved in 2019, and introduced a series of rules with the aim to adapt the European legislation to a new landscape, in which a new set of actors like independent aggregators, and active consumers coexist with the traditional energy actors. While most of the provisions of the Regulation were immediately applicable with its publication, several provisions set in the Electricity Directive are still a work in progress. As an example, article 59(e) of Directive (EU) 2019/944 mandates the EC to adopt rules for implementing cooperation between distribution system operators and transmission system operators, DR through aggregation, incentives for the use of flexibility in distribution and transmission networks as well as marked driven rules for storage facilities in distribution and transmission networks. What is more, Article 32 of the Directive also introduces the role of DSOs to procure flexibility services provided by distributed energy resources including demand response and energy storage based on market mechanisms, to efficiently operate their grid and limit costly grid investments and expansion. Nevertheless, the framework for flexibility use from demand side is not fully specified in the current network codes and regulatory frameworks. Some barriers still exist for the development of demand-side flexibility, for example, requirements in the existing network codes that do not cover the whole scope of products and services for the provision of flexibility and concerning the role of distribution system operators, or the limited standardization and harmonization at EU level. Therefore, a clear framework must be put in place for flexibility mechanisms, starting with a clear roadmap for the use of flexibility at all systems. Those regulatory gaps in the existing regulations have to be solved to procure the right design for a congestion management market which provides new services for resilience. The Electricity Regulation envisages the development of EU NC in different areas, based on a priority list established every three years. Implementing Decision (EU) 2020/1479 of 14 October 2020 establishing priority lists for the development of network codes and guidelines for electricity for the period from 2020 to 2023 and for gas in 2020, specifies that "the priority list for the development of harmonized electricity rules for the period from 2020 to 2023 shall be the following: [...] (b) rules regarding demand side flexibility, including rules on aggregation, energy storage and demand curtailment rules"[94].

[94] DECISIONS COMMISSION IMPLEMENTING DECISION (EU) 2020/1479 of 14 October 2020 establishing priority lists for the development of network codes and guidelines for electricity for the period from 2020 to 2023 and for gas in 2020, Official Journal of the European Union, 15.10.2020, L338/10.

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