OSMOSE

Final Report

OSMOSE
OPTIMAL SYSTEM-MIX OF FLEXIBILITY

Foreword

After four years of collaborative research, development and demonstration activities, the OSMOSE project comes to an end in April 2022.

This report aims to give an overview of the challenges addressed, the work performed, and the main achievements reached by the consortium when tackling the vast and complex question of power system flexibility.

We would like to thank all the partners for their active involvement in this project and the great results obtained. They contribute to a better understanding and implementation of power system flexibility to support the European energy transition.

We thank the European Commission for funding this work under the Framework Programme Horizon 2020.

Project key figures

START DATE

January 2018

END DATE

April 2022

TOTAL BUDGET

27,2 M€

EUROPEAN GRANT

21,2 M€

33 partners

INCLUDING ACADEMICS, TRANSMISSION SYSTEM OPERATORS, EQUIPMENT MANUFACTURERS, RENEWABLE ENERGY PRODUCERS, AGGREGATORS AND IT EXPERTS.

9 countries

COORDINATOR

RTE, France

Figure 1. OSMOSE partners by country.

BELGIUM

FRANCE

ITALY

GERMANY

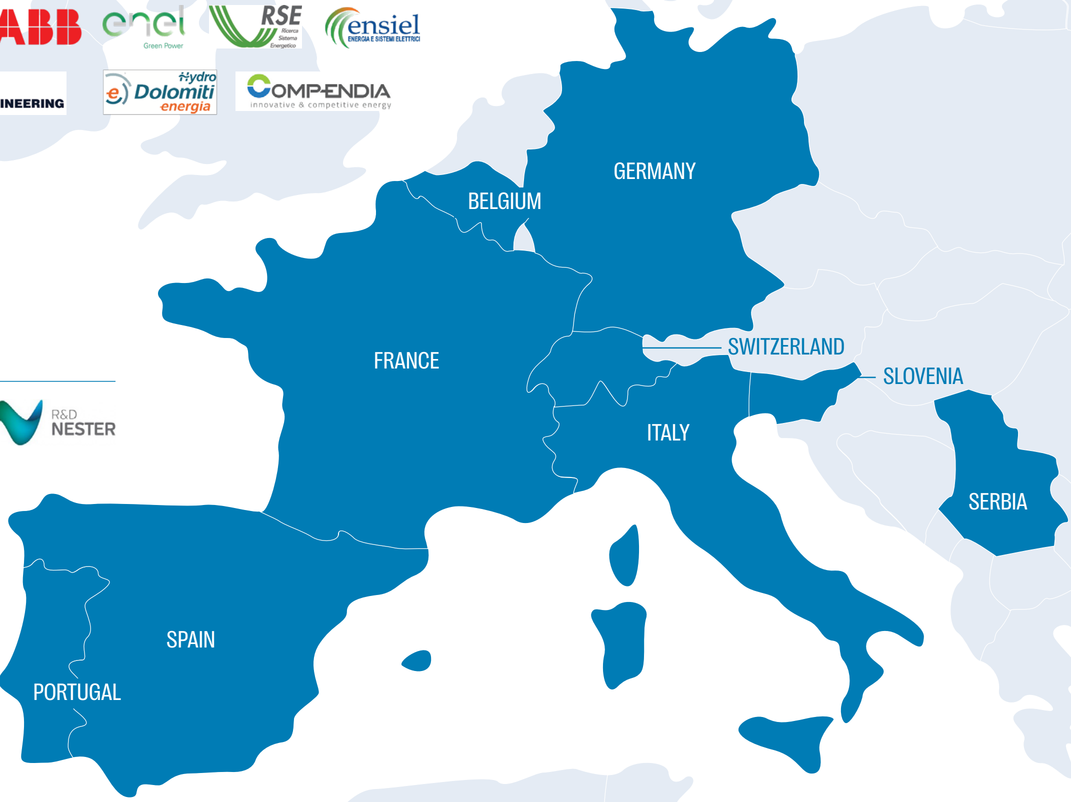
PORTUGAL

SLOVENIA

SERBIA

SPAIN

SWITZERLAND



Executive summary

The OSMOSE project aimed to improve the understanding and consideration of flexibility needs and resources in future power systems. The 33 partners implemented four large-scale demonstrators under the leadership of Transmission System Operators (TSOs). In parallel, they worked on three theoretical Work Packages (WP) dealing with modelling and standardization.

Figure 2. OSMOSE Work packages and demonstrators' main features.

WP1. Optimal mix of flexibilities

System planning models | 2030-2050 scenarios

WP2. Market designs & regulations for optimal development of flexibilities with high RES shares

Forecast errors | Market models

WP7. Scaling up and replication

Interoperability | TSO-DSO coordination | BESS design & data analytics

Demo WP3

Grid forming for the synchronisation of large power systems by multi-service hybrid storage

- Supercapacitors 1 MW-10 s
- 0.5 MVA-60 min Li-ion battery
- Ingeteam lab

- 720 kVA/560 kWh LTO battery
- 25 kWh LOT battery
- EPFL campus

Demo WP6

Near real-time cross-border energy market

- Soverzene plant – 20 MW – ENEL
- Santa Massenza plant – 70 MW – HDE
- DEM, TES and SENG plants – 135 MW – HSE
- High voltage grid – TERNA & ELES

Demo WP4

Multiple services provided by the coordinated control of different storage and FACTS devices

- STATCOM 4 MVar
- Supercapacitors 0.8 MW
- 1500 V Li-Ion batteries (2 MW/0.5 MWh)

- CENER 20 kV grid-connected facilities
- Different batteries

Demo WP5

Multiple services provided by grid devices, large demand-response and RES generation coordinated in a smart management system

- 5 industrial consumers – ~120 MW of flexibility
- 2 wind farms - 53 MW – +1 battery (2 MW - 2 MWh) – ENEL, E2i
- 7x150 kV lines – Dynamic Thermal Ratings – TERNA

Demonstrating Battery Energy Storage System and converters flexibility

Battery Energy Storage System (BESS) are technically very efficient in providing support to the system thanks to their high flexibility. However, their high cost compared to other flexibility solutions remains a barrier to their deployment and some of their capabilities were still to be investigated. In that perspective:

- ✓ WP4 demo developed a **new hybrid flexibility device** integrating a utility-scale lithium-ion battery, supercapacitors and a modular multilevel static compensator. Its architecture used standard components able to reach higher voltages, reducing current and therefore losses, allowing flexibility and compactness.
- ✓ The **lithium-ion battery,** developed within the project, **supplies high-voltage power output** (1260 Vdc), enabling significant cost and power loss reductions, as well as enhanced power quality.
- ✓ **WP4 and WP3 both demonstrated advanced controls for multi-services provision by BESS.** The first one focused on multiple device coordination and ageing limitation. The second addressed the stochastic behaviour of the services and the real time capability curves of the converter.
- ✓ **WP7 investigated methods to optimise the sizing and the control design of BESS.** A database with **new data analytics tools** was also developed to support the sharing of experience between BESS operators.
- ✓ **WP3 investigated how off-the-shelf converters can contribute to the fundamental stability of the system thanks to grid forming controls.** The ability of grid forming to respond to grid disturbance within 5 ms was demonstrated without impacting the converter size and the provision of other services. Methods to certify and assess the grid forming capability were developed and synchronisation services were defined to feed in future grid codes.

Key takeaways

- ✓ Due to their criticality for system stability, the mandatory provision of synchronisation services should be investigated when it implies no additional cost for the providers. Anticipating their implementation on the converters connected to the grid is necessary to prevent scarcity of synchronisation services in the future European system or high retrofit costs.
- ✓ Battery Energy Storage Systems can now compete with other existing flexibility solutions to support system security and stability. Specific designs and controls tailored for system services make them all the more cost-effective in specific situations such as isolated systems.

Demonstrating RES and industrial flexibility

While the flexibility potential of RES and demand sources is acknowledged in the literature, significant implementation gaps still prevented their effective contribution in the daily operation of the power system. To foster this integration, **WP5 demonstrated in Southern Italy:**

- ✓ **The provision of Automatic Voltage Control (AVC) by wind farms.** An upgrade of two plants' controls enabled AVC, however with some delay of up to 60 seconds in the provision, since the control system had not been originally developed for this type of regulation.
- ✓ **The provision of Synthetic Inertia (SI) by two wind farms.** The main innovation laid in the Synthetic Inertia Control Device (SICD) implemented and the measurement and filtering algorithm to provide response within 500 ms. Laboratory test bench simulations on wind turbine components also provided an insight on the possible inertial-like power contribution a wind turbine could provide for frequency support.
- ✓ **The provision of ancillary services by 5 industrial loads.** Although successful, the required plants' retrofitting was complex and the flexibility that could be activated was rather limited.

In WP6, the near real-time potential of flexibility of hydro producers was explored. New tools were developed and live demonstrated to estimate their remaining flexibility 15 min before delivery time.

Key takeaways

- ✓ The provision of ancillary services by wind farms is technically possible but some implementation gaps remain for their daily effective use. TSOs - through grid code evolution - and manufacturers – through industrial development - should accelerate their efforts to avoid scarcity of ancillary services or high retrofit costs in the coming years.
- ✓ Industrial loads can provide flexibility to the system but with a limited potential due to their already optimised industrial processes and with significant retrofitting challenges. Harvesting this flexibility potential for fast regulations should probably not be the priority in the coming years, while they can be counted on for slower regulations.

Demonstrating grid flexibility and efficient coordination

The grid itself can offer significant flexibility to the system through advanced equipment and controls. The proper coordination of the grid and all other flexibility levers in system operation is key to benefiting from their full potential. In that perspective:

- ✓ **WP5** demonstrated the flexibility potential of the grid thanks to the deployment of **Dynamic Thermal Rating (DTR) in seven high Voltage Lines** in Southern Italy, and the installation of **an innovative smart Energy Management System** (EMS) in the TSO control room.

- ✓ **WP6** demonstrated the possibility of **cross-border flexibility activation near-to-real time while respecting grid limitations.** The developed tools and processes resulted in a real cross-border activation thanks to a selection of bids every 5 minutes and an activation signal sent every 10 seconds.

- ✓ WP7 developed a tool to enhance **voltage control by optimising the flexibility levers at the TSO/DSO interface and at distribution level.**

- ✓ WP7 defined and demonstrated **improvements of the IEC 61850 engineering process** for substations. They standardise the exchange of information between the system operators and the equipment vendors.

Key takeaways

- ✓ Advanced sensors and tools like advanced Energy Management System can improve the operation of the grid in congested areas. They are significant opportunities for TSOs to optimize their operational cost, although their deployment induces challenging adaptations in already complex industrial environment and practices

- ✓ Close to real time cross border exchanges are challenging from an IT perspective but technically feasible while complying with grid constraints and thus ensuring system security. However the economic value of the hydro producers' residual flexibility after existing gate closures remains limited in the actual system. A large deployment of this concept should only be considered when higher RES penetration will call for more close to real time flexibility.

Modelling and quantifying future flexibility

The long-term picture of the contribution of each technology in the future electricity mix is difficult to depict as many uncertainties exist on technologies, social and political orientations. However, advanced quantified studies and simulations are crucial to support investment and market design decisions. In that perspective, OSMOSE worked on enhanced studies and modelling of flexibility:

✓ WP1 developed new tools and methods to capture the issues of **flexibility in capacity expansion models** since they turned out to be under-evaluated. **Scenarios for the European System until 2050** were created and provided insights on future needs and sources of flexibility.

✓ WP2 achieved significant progress in the **modelling of forecast errors, day-ahead and intraday energy market processes. Simulations of 2030 scenarios** showed the growing role of intraday markets and the contribution of the different flexibility sources to addressing forecast errors.

Key takeaways

✓ Advanced simulations of the European power system are essential to support decisions on investment plans, incentives schemes and market design with quantified evidence.

✓ All flexibility needs and sources are closely interrelated and should be taken into account in long-term studies. The use of various existing simulation tools is necessary to capture the different aspects of flexibility while considering all time scales (from long-term planning to system operation) and sector coupling.

✓ Future policies should ensure the best use of the flexibility potential of power to gas, batteries, RES and grid. They all have a critical role to play in the coming power system and their optimal coordination close to real time brings significant value to address increasing variability and uncertainty.

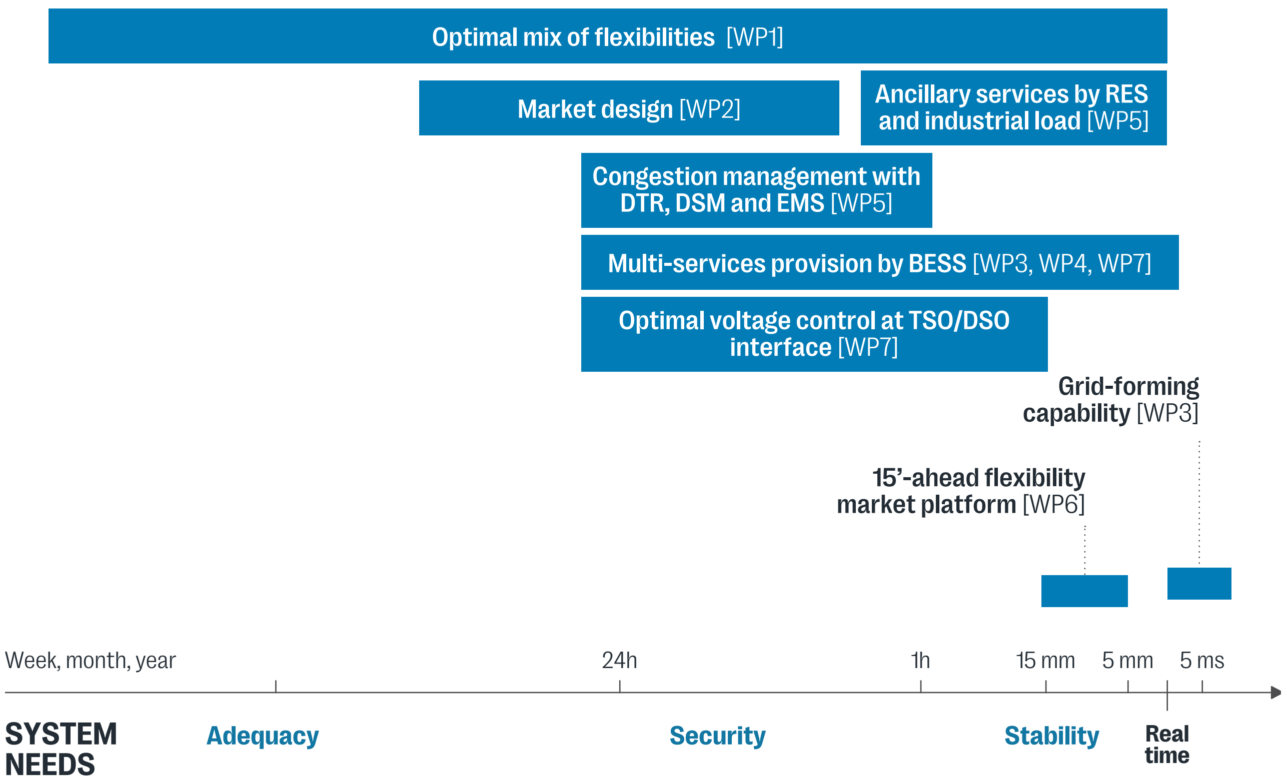
OSMOSE contributed to various and complementary aspects of power system flexibility [Figure 3] showcasing that the decarbonisation of the European power system is at reach: new flexibility challenges are rising but there are many promising options to tackle them. The optimal combination of such options can address the different types of system needs.

Still, the demonstration of some of those innovative solutions highlighted remaining gaps for their effective implementation. They can for sure be solved but TSOs, producers, manufacturers and policy makers need to accelerate their deployment to avoid flexibility scarcity in the coming years and ensure the achievement of EU targets.

The large scale demonstrations also showed that evolutions in the operation of the power system are challenging due to technical complexity, multi-actors involvement and the need of high reliability and security. Efforts should be concentrated on technological or process evolutions that proved the most promising based on quantified impact assessment.

Last but not least, EU projects are a successful example of framework to co-design solutions suitable to address systemic challenges with different actors, each bringing knowledge on its constraints and opportunities.

Figure 3. Summary of the flexibility issues addressed by OSMOSE depending on their time horizon ahead of real-time system operation.



Contents

Introducing flexibility

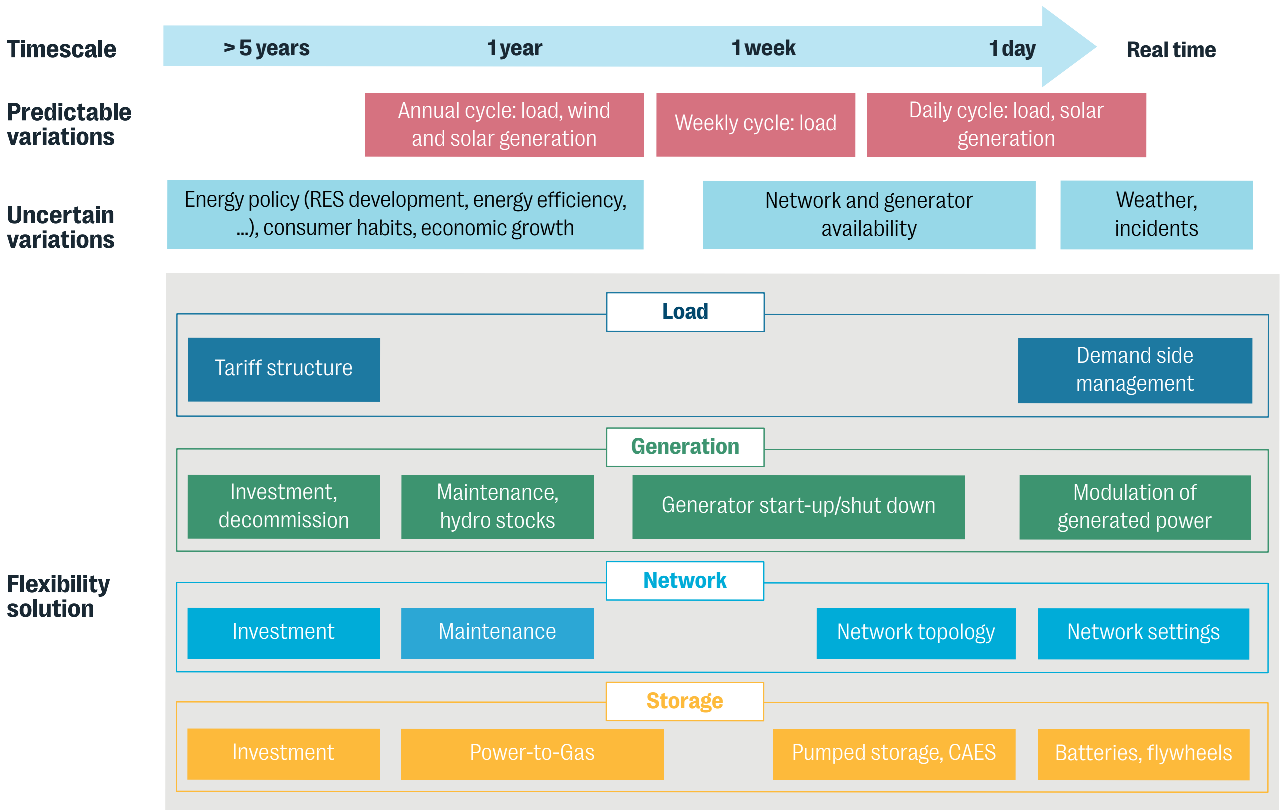
Many definitions of flexibility exist in the literature, some focusing only on short-term issues, others covering only specific flexibility sources like demand. On the contrary, OSMOSE promoted a holistic definition of flexibility: “power system flexibility is understood as its ability to cope with variability and uncertainty in demand, generation and grid, over different timescales.” Indeed, all the time horizons are fundamentally interrelated and all the components of the system can contribute to its flexibility. A global understanding is thus critical to capture synergies.

The power system has always required flexibility to address uncertainty and variability and, in the past, it was mainly provided by thermal and hydro plants. However, the on-going evolutions are triggering both new needs and new sources of flexibility:

- ✓ Renewable Energy Sources (RES) drastically reshape the variability and uncertainty in the system but they can also contribute to its flexibility.
- ✓ Inverter-based generation replace the synchronous generators, challenging system stability but also bringing new opportunities of fast and advanced controls.
- ✓ New electrified end uses - heating, mobility – can create additional load peaks but can also provide flexibility if managed in an intelligent manner.
- ✓ Large storage solutions are becoming more competitive, offering new perspectives for flexibility provision.
- ✓ Advanced automation and control technologies enable smarter and faster activation of flexibility solutions.

The OSMOSE project contributed to shape the future system flexibility by demonstrating some of these new technological solutions and understanding future needs and resources in prospective scenarios.

Figure 4. The flexibility question across time horizons.

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Demonstrating energy storage system and converter's flexibility

Energy Storage System (ESS) are technically very efficient to provide flexibility services to the grid and support the system operation. However, their high cost compared to other flexibility solutions is still a barrier to their deployment in multiple cases. OSMOSE brought some achievements both at design and operational stages to maximise the value of ESS. Furthermore, the project investigated how inverter can contribute to the fundamental stability of the system thanks to grid forming controls.

1.1 The design of electricity storage systems was improved to decrease their cost

A new utility-scale lithium-ion battery with high-voltage output was developed by Saft enabling costs reduction

In WP4, Saft developed and validated a utility-scale lithium-ion battery with high-voltage output. Compared to conventional 690 Vdc output batteries, this shift to 1500 V class enabled the use of latest-generation power conversion systems derived from the PV industry. The main advantages for high-voltage, utility scale storage systems are the following:

- ✓ Use of larger (up to 4.5 MW), cheaper and more efficient power conversion units, thanks to the higher power conversion output voltage (up to 690 Vac compared to 480 Vac previously) of 1500V-class Power Conversion System (PCS). Those Larger PCS systems also optimise the overall footprint and operational costs during the lifetime of the project.
- ✓ Overall reduction of power losses of 20 % to 40 % depending on PCS technology and system size, due to higher conversion efficiency, lower auxiliary consumption- and reduced cabling of fewer conversion units.
- ✓ Enhanced power quality, due to 3-level conversion instead of conventional 2-level conversion.

At battery level, this voltage shift was achieved through major modifications of the existing architectures (electronics boards module, centralised electronics, battery wiring to sustain the voltage insulation, electrical power distribution). The 1500 V battery technology is now commercialised by Saft, enabling them to extend their product range beyond their previous 1000 V limit.

A modular hybrid flexibility device integrating power electronics and different energy storage equipment was developed and demonstrated

In WP4, CENER, GPTECH, REE, Saft and ULPGC successfully designed, implemented and tested a Hybrid Flexibility Device (HFD) for the provision of multiple grid services. This hybrid flexible device was composed of:

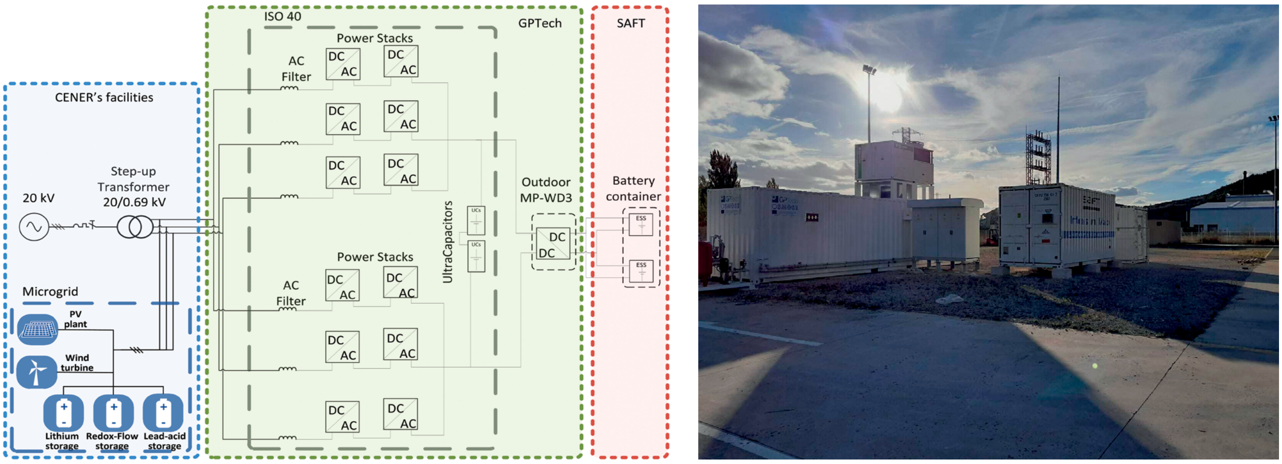
- ✓ Static Compensator (STATCOM) based on 12 Modular Multilevel Converters up to 4 MVar
- ✓ Two Supercapacitors providing up to 800 kW
- ✓ A containerised 2 MW/0.5 MWh Li-ion battery (the one developed by Saft)
- ✓ A DC/DC power converter coupling the STATCOM with the battery

Compared to traditional technologies, the main advantages of the hybrid device concept are its modular architecture and the hybridization of the STATCOM with the new battery system as well as the supercapacitors.

This solution replaces traditional passive elements (large capacitor banks and/or reactance required to compensate reactive) with a more compact and smaller design thanks to power electronics use.

Therefore it allows the employment of already existing electrical infrastructures, or of new indoor/outdoor installation using container structures without large space requirements.

Figure 5. Diagram (left) and real picture (right) of the HFD installed in in the demonstration location.



This HFD was installed on CENER facilities in 2021 for 6 months of tests. The solution is close to commercialization and some further R&D is planned to achieve Technology Readiness Level 9.

The progress and results obtained in the demonstrator will be essential to evaluate the future installation of a similar device in the Canary Islands power system by REE. Simulations performed by the University of Las Palmas of Gran Canaria and REE demonstrated the positive impact this device could have on frequency, voltage control and congestion management enabling further integration of RES on the islands. The service provision capability of this device is further explained in section 1.2.

ⓘ **[D4.3] [D4.5]**

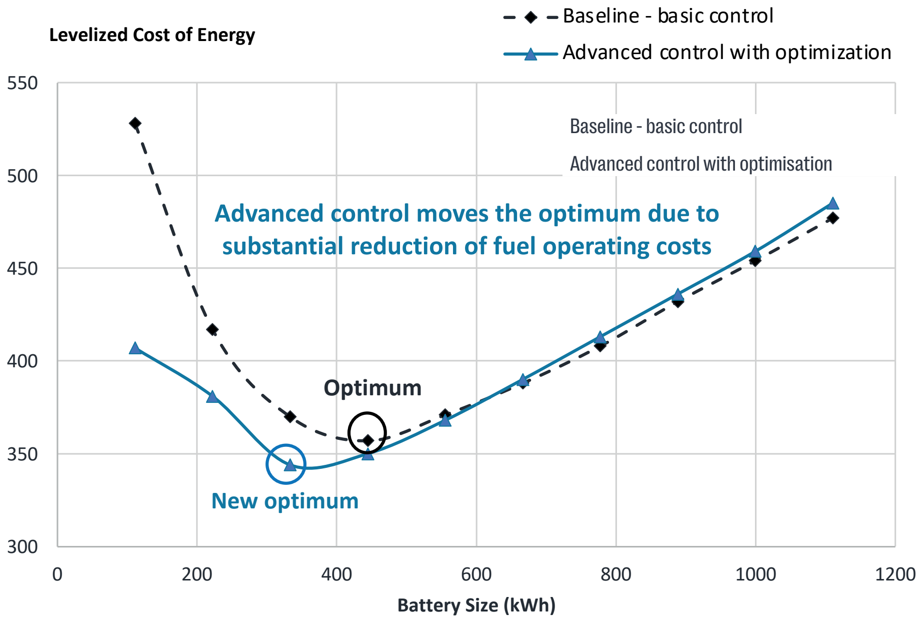
New tools were developed and tested to optimise Battery Energy Storage System sizing and design according to application and ageing

Within WP7, CEA developed a simulation-based methodology for the optimal sizing and design of BESS by taking into account both the application and the storage performance over its lifetime. Applied to different use cases, the methodology enabled to distinguish, among the influencing factors investigated through sensitivity analysis, that:

- ✓ Optimal sizing does not require a high degree of technical modelling.
- ✓ The influence of the simulation time-step on optimal sizing strongly depends on the application time constants related to the events impacting the operation costs or incomes.
- ✓ Different control strategies may lead to a different optimal BESS size: it is recommended to clearly define the control strategy before determining the optimal size as illustrated in Figure 6 below.
- ✓ If the main function of BESS is to compensate for forecasting errors of RES, forecast quality is of the highest importance for optimal sizing: one case study showed that a 50 % improvement of the forecast quality induced a difference of 15 % of the sizing indicator value.

ⓘ **[D7.5] [3]**

Figure 6. Optimal BESS sizing in one of the tested case with a basic control and an advanced one. The optimal size is impacted by the control modelling which should thus be considered carefully at the sizing stage.



BESS safety is a critical factor to be considered

Safety of BESS is also an issue to be carefully considered since one demonstrator of the WP3 faced a fire during the Site Acceptance Tests in RTE substation. There were no injuries and no other damage than the impacted container but the experimentation could not be continued during the project duration. To learn from this experience, some details and recommendations are given in public deliverable 3.3.

ⓘ **[D3.3]**

1.2 Service provision by electricity storage systems was optimised to increase their benefits

To improve the economic performance of ESS, their operators need to diversify and optimise their provision of system services. Advanced controls are necessary to maximise this multi-service provision while considering the limits of the equipment, their ageing, the uncertainty of the real-time system needs and also ensuring a sufficient reliability since some services are critical for the system. Two multi-services control of storage systems were developed and demonstrated in the OSMOSE project, each featuring significant innovation to address those challenges.

WP4 demonstrated a master control of different storage equipment providing multiple grid services while minimising their ageing

In WP4 demo led by REE, a Master Control (MC) was developed by CENER and tested on real environment at CENER facilities. This Master Control coordinates the response of the new Hybrid Flexibility Device developed in WP4 (defined in Section 1.1) in combination with other energy storage systems already existing in the demonstrator in order to provide multiple grid-services. Technical devices' features and services priority are considered in the optimal performance while ageing of the battery systems involved is minimised.

The operator can configure and activate the different flexibility services classified in three control levels depending on the grid service purpose (see Figure 7). To reserve capacity and energy for the critical services of the levels 1 and 2, the operator can define configurable energy and power limits.

Figure 7. Description of the 3 levels of Master Control (left) and power/energy distribution depending on the limits defined by the user.

	1st LEVEL	2nd LEVEL	3rd LEVEL
Objective of the controls at each level	To provide grid stability support services	To provide voltage and frequency control services once grid stability has been guaranteed	To optimize the management of the flexibility devices, taking into account the nature and characteristics of the devices it manages
Operated by MC	No	Yes	Yes
Services and functionalities	• Inertia emulation (A) • Fast Fault Current Injection (A) • POD (A) • P-f regulation (trapezoidal response) (A) • P-f regulation (primary frequency regulation on disturbed condition) (A)	• P-f regulation (continuous primary frequency regulation) (B) • Voltage control (D) • Q setpoint (D)	• Setpoint tracking (C) • Program management (C) • Congestion management (D)

For the 2nd and 3rd levels, the Master Control is then able in real-time to:

1. Distribute the required power and energy among the different energy storage equipment available, taking into account the impact on their degradation and lifetime. Indeed, for storage systems, operation at extreme power or State-Of-Charge (SOC) on a frequent basis can lead to accelerated degradation of the device. The Master Control can take advantage of the complementarity of the different storage equipment to minimize those extreme solicitations. This feature highlights the interest to coordinate the operation of multiple storage system.

2. Manage the SOC of the storage equipment over time to maximise the availability of power and energy in order to respond to the functionalities required, given their

possible future activation. Indeed, a reliable provision of some services is critical for the security and stability of the power system.

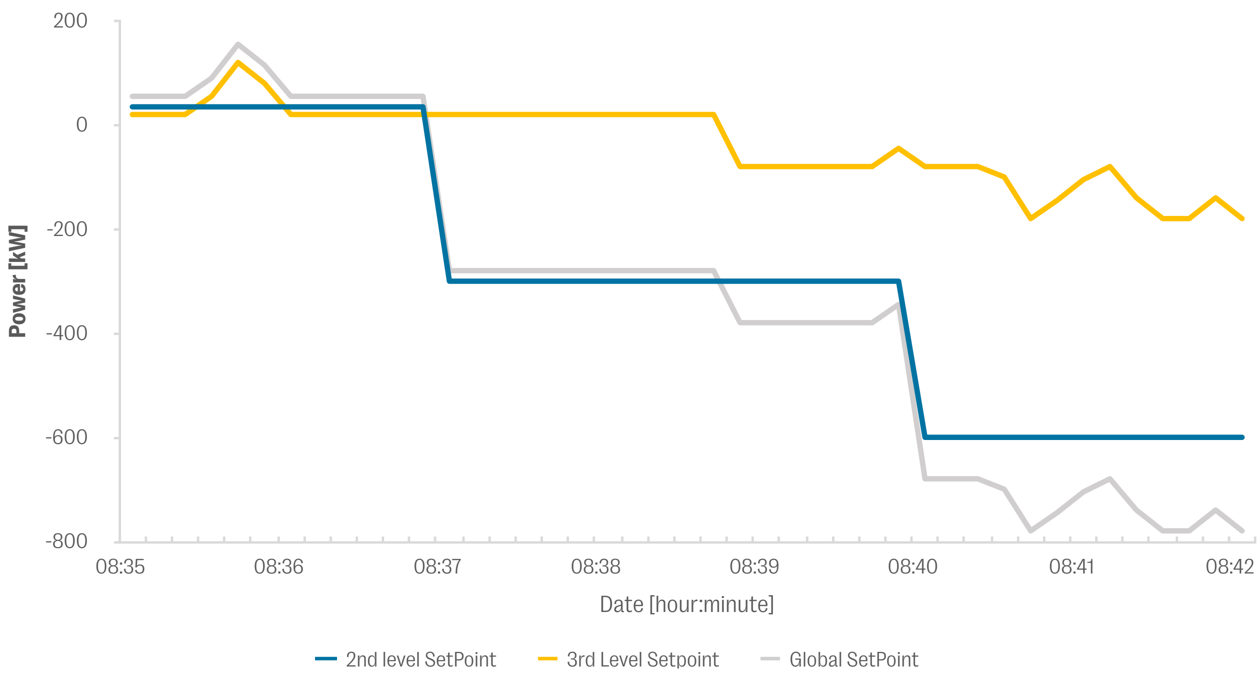
Simulations and demonstration at CENER facilities of the effectiveness of the Master Control were performed with the following equipment connected to the 20kV AC grid through a 0.690/20 kV transformer:

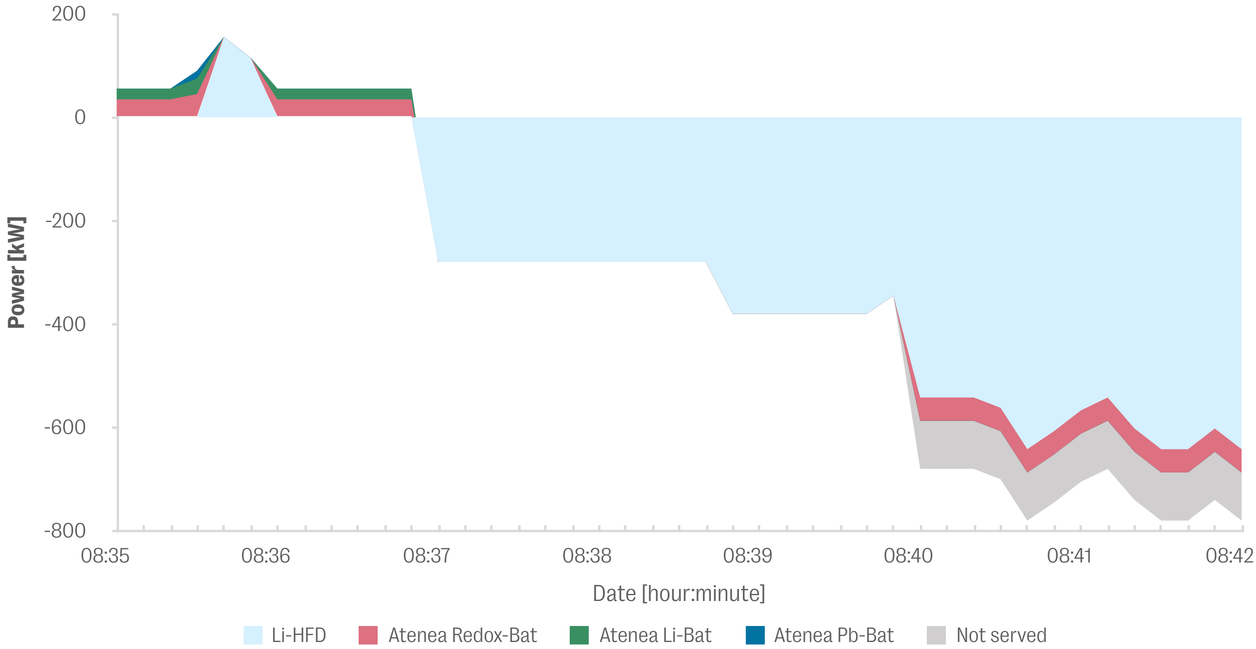
- ✓ An innovative 4 Mvar hybrid flexibility device (BESS + supercapacitors + STAT-COM) [see section 1.1]
- ✓ A 50 kW/100kWh Lead acid gel technology battery bank (Pb-bat Atenea)
- ✓ A Stationary 30kW/43kWh Lithium-ion battery (Li-Bat Atenea)
- ✓ A 50kW/200kWh Vanadium Flow Battery (Redox-Bat Atenea)

Notably, the developed master control is independent of the underlying technology, and highly configurable. Therefore it could be suitable for another set of equipment. REE investigates the possibility to use this Master Control on the Canary Islands.

ⓘ **[D4.4] [D4.5]**

Figure 8. Simulation of the 2nd and 3rd level requirements and related power split between storage devices by the Master Control.





WP3 demonstrated a three-layer BESS control strategy from day ahead to real-time optimising the provision of multiple grid services under uncertainties

In WP3 demo, EPFL validated a control framework for set-point tracking and provision of ancillary services by a BESS taking into account grid measurements, BESS status and converter capability curves. The demonstration was implemented on a 720 kVA/500 kWh Lithium Titanate BESS, connected to a 20 kV distribution feeder on the EPFL campus hosting also stochastic loads and PV generation. The control framework relies on three complementary optimisation problems solved for different time horizons:

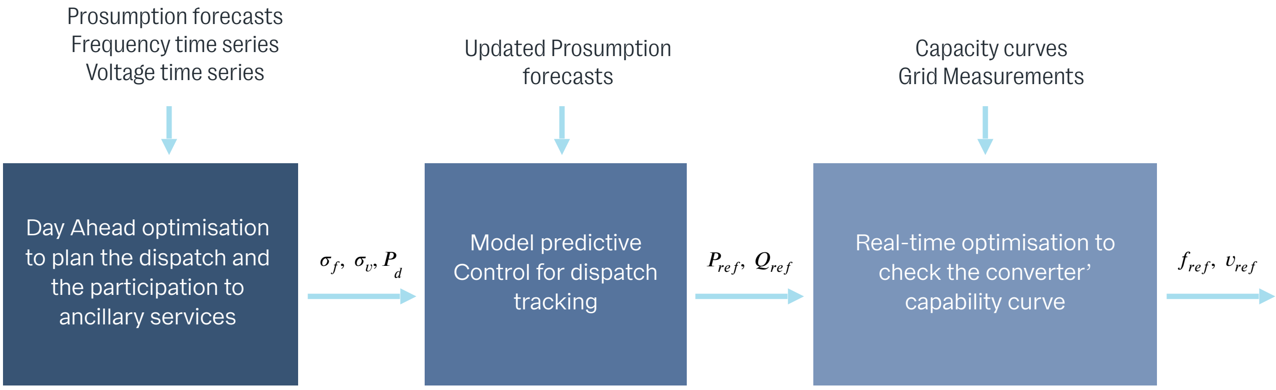
1. Day-ahead: The needs for the different services are estimated to schedule an optimal allocation of multiple services based on the notion of power and energy budget for each of them. For the demo, the services considered were frequency control, voltage control and day-ahead dispatch. This feature can be used by the BESS operator to offer capacities to the market or the system operator on a daily basis.

2. Intra-day set-point tracking: In the intra-day phase, the control set-points of the various services are calculated separately and superimposed. Uncertainties over the future time steps are accounted in a suitably defined Model Predictive Control framework fed by short-term forecasts. This enables to reliably deliver the scheduled services which is critical to limit penalties for non-provision of services and, of course, to ensure the overall system security.

3. Real time: The real time controller takes into account the PQ region of feasibility of the BESS power as a function of the battery DC-link and AC grid status. This feature is fundamental to avoid the tripping of the BESS power electronic interface since it guarantees, a-priori, the feasibility of the control set point.

This framework differs from the existing literature on several aspects: i) the generic formulation of the scheduling problem that can accommodate any kind of service, ii) it has a technical rather than revenue-driven control objectives, iii) the consideration of the stochastic behaviour of the services deployment and exploitation of robust optimisation techniques to hedge against uncertainty and achieve reliable real-time operation and iv) the real time consideration of the PQ region of feasibility of the BESS and its power electronic interface.

Figure 9. Scheme of the three-layer BESS control strategy demonstrated by EPFL.



$$P = P_{ref} + \sigma_f \bullet \left(f - f_{ref}\right)$$
$$Q = Q_{ref} + \sigma_v \bullet \left(v - v_{ref}\right)$$

During the demonstration, a frequency regulating power up to 117 kW was provided on top of the normal dispatch operation of the 720 kVA/500 kWh Lithium Titanate BESS with a very limited tracking error, demonstrating the effectiveness of the control framework devWeloped.

[D3.1] [D3.4] [4] [5] [6]

Enhanced BESS modelling can improve their design and control

Experience often shows a strong deviation between theoretical and real BESS performance, for which too basic control is accountable. In WP7, CEA developed mathematical models of batteries to better consider aging and efficiency at both scheduling and real-time stages. Especially, the following factors can influence the optimal control:

- ✓ Limited power of the charge/discharge depending on the State of Energy (SOE)
- ✓ Losses depending on the power of the charge/discharge
- ✓ Ageing decoupled into calendar ageing and cycling ageing

The developed battery models allow a configuration of these phenomena with the requested level of accuracy. They have been used to simulate optimal control for hybrid power plants (PV + Storage) projects, for battery providing system services and to perform BESS optimal sizing. Other electrical infrastructure models that can provide flexibilities, such as hydrogen storage or electric vehicle charging stations have also been developed.

ⓘ **[D7.5]**

Data sharing and analytic tools enable to improve ESS operation

While the number of ESS connected to the grid increases, operators are still lacking experience and feedback to better understand their behaviour. This can be a barrier to their exploitation and spread. CEA and EPFL thus developed platforms to collect, store and share measurements data from on-field ESS, coupled with data analytics to support BESS operation through diagnostic and prognostic analyses, performance evaluation and control improvements.

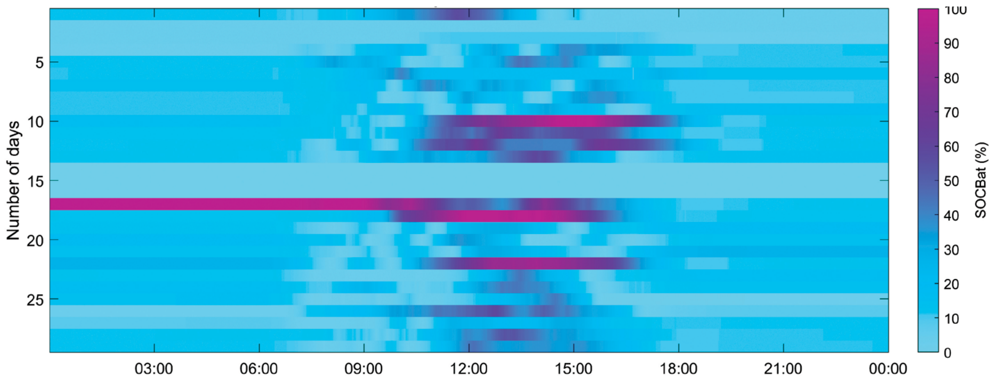
The data analytics tools developed in WP7 integrate among others a novel method to identify the BESS equivalent circuit model parameters without requiring any specific tests, along with a strategy to identify the factors impacting the aging processes. This method was validated using real-time measurements of the utility-scale BESS of WP3 demo during its operational phase providing various grid services. The tools also calculate the BESS efficiency and state of health without dedicated tests and through several state-of-the-art methodologies. Additionally, to get the current status of BESS performances, it can be used for instance to predict by simulation the evolution of such parameters based on the historical use of the BESS. The associated database and information system provide graphical representations of BESS use and performances on the service(s) supplied. Two patents on data analytical tools were submitted by CEA.

This data base is hosted by the CEA. It will be maintained after the project's end and ESS operators are welcomed to join in.

ⓘ **[D7.7] [D7.8]**

Figure 10. Screenshots from the database tool.

Heatmap of BESS1 State of Charge



1.3 Grid forming capability of BESS was demonstrated and paves the way to future grid codes

In traditional power systems, synchronous generators maintain frequency and voltage thanks to their physical inertia, voltage source nature and their implemented local controllers. The increasing penetration of renewables, usually interfaced to the grid via power electronic converters, challenges this approach to ensure system stability.

New types of converters controls, called grid forming (in opposition to "grid following" controls), have emerged in the literature in the past years, notably in the former H2020 project MIGRATE which inspired OSMOSE WP3. Implemented on the converters of renewable generators, batteries or HVDC links, grid forming controls lead to an immediate stabilising response to phase, frequency and voltage amplitude changes, thus supporting system stability.

Precise and common definitions of grid forming capability and synchronisation services are necessary to update grid codes and anticipate future provision mechanisms

Based on the project works and a state of the art of current definitions around the world, WP3 proposed definition of grid forming (GFM) capability and synchronisation services:

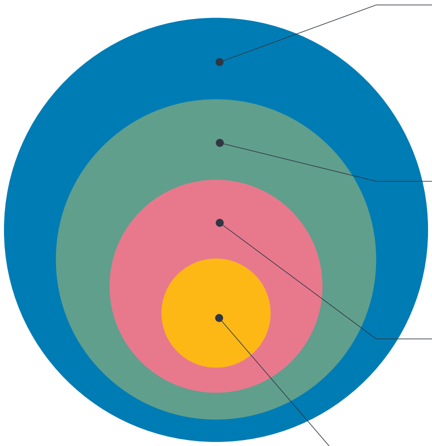
- **A grid forming** unit shall be capable of **self-synchronisation, standalone and provision of synchronisation services,** which means that it does not rely on grid conditions to synchronize and will help other units to maintain synchronism, while still complying with other general requirements applying to the specific technology.
- **Synchronisation services** encompass the following features: **Synchronising active power, inertial response, system strength, fast fault current injection.** The provision of each service is characterised by an immediate response (<5 ms) following a grid change, other technical requirement, such as the amplitude of the response or the maintain time might depend on the system needs.

From grid forming controls existing in the literature, WP3 proposes to define four "types" of unit depending on their capability to provide the different synchronisation services, each having a different criticality in the coming years [Figure 11]. A synchronous machine is, by construction, a type 4 GFM unit and the WP3 demonstrators are voltage source converter (VSC)-interfaced ESS that fall in the type 3 category.

The future provision mechanisms for those services in Continental Europe still need research to answer questions such as: Where/When/How much/For how long do we need each service? However, the grid forming capability should be anticipated as soon as possible in grid connection codes to ensure sufficient future availability of this critical capability.

ⓘ **[D3.3]**

Figure 11. Four types of grid forming depending on the services provided, OSMOSE demonstrated Type 3.



TYPE 4	Services provided: Type 3 + Fault current above 2 times the Nominal Current Criticality: if protections fail to detect faults Cost: high for converters since they have to be oversized, null for synchronous generators
TYPE 3	Services provided: Type 2 + Inertial response Criticality: When system inertia decreases globally Cost: limited due to the need of an energy buffer from a few seconds to 1 min
TYPE 2	Services provided: Type 1 + Synchronising power profile Criticality: When system inertia decreases locally Cost: very limited due to the need of an energy buffer <1 s. Other FFR resource are supposed to be available elsewhere.
TYPE 1	Service provided: Stand alone + System strength, Operate wide range of SCR Criticality: When system strength decreases locally Cost: null, only software

BESS can perform grid-forming without impacting the other services provided and the converter sizing

To enable a wide adoption of grid forming controls at a limited cost, the following questions needed to be addressed: Can they be implemented on off-the-shelf equipment? Can they be compliant with the converters current limits without oversizing it? Can the BESS keep providing other services normally on top of grid forming? To those three questions, WP3 answered positively thanks to two demonstrators:

- ✓ EPFL implemented grid forming control on a pre-existing off-the-shelf converter coupled to a 720 kVA/500 kWh Lithium Titanate BESS, connected to a 20 kV distribution feeder of the EPFL campus. Grid forming was successfully provided on top of other services (voltage and frequency regulation and dispatch tracking).

- ✓ Ingeteam and RTE implemented grid forming control on in a 1 MVA rated power fully containerised hybrid ESS which includes four lithium-ion battery racks (0.5 MVA-60 min) and two times three ultra-capacitor (UC) racks (for a total of 1 MW-10 s). This hybrid architecture enabled to test different strategies of DC power sharing, especially to put the burden of fast transients on the UC instead of the battery. Factory Acceptance Tests were performed using a power hardware in the loop (PHIL) test bench connected to a virtual grid located in Ingeteam power laboratory facilities.

Figure 12. Inside the EPFL battery (left) and Ingeteam test environment (right).

To ensure the robustness of the control under unbalanced voltage faults (an issue that has received limited attention so far in the literature), INGETEAM and RTE developed a current limiting method based on the Negative Sequence threshold virtual impedance (NS-TVI) that keeps the voltage source behaviour associated to the grid forming capability, even when the current limit is reached, while reducing the voltage unbalance according to user-defined settings. To ensure a wide uptake by the industry, the performed controls upgrades are detailed in public deliverables and in an open access article. This is the first time MVA scale VSC experimental results of grid forming for a wide range of tests are published. They will feed in future work focusing on the implementation of connection requirements and fine tuning compliance criteria and procedure.

ⓘ **[D3.3] [16] [17] [18]**

Grid forming responds in less than 5 ms and its performances can be assessed externally thanks to new metrics

To enable future certification and assessment of grid forming provision, specific methods are necessary to discriminate this capability based on output measures and without knowledge of the inside control implementation. This is particularly challenging for demo-scale installations connected to the strong European grid (high short-circuit power).

EPFL proposed two metrics for that purpose: Relative Rate-of-Change of Frequency and Relative Phase Angle Difference Deviation using high accuracy Phasor Measurement Units (PMU). They were effectively used in the demo to highlight the superior performance of grid-forming control for frequency smoothing thanks to the provision of an inertial response, compared to the grid-following one.

To scale-up this finding, simulations were performed on a modified low-inertia IEEE 39-bus benchmark network released open source. Results demonstrated again that grid-forming controlled BESS outperforms the grid-following one in improving the system frequency containment. Grid forming achieves to provide active power in less than 5 ms for phase jumps and frequency variations. In comparison, Fast Frequency Response (FFR) or Synthetic Inertia (SI) can physically not respond quicker than a few hundreds of milliseconds (~400 ms for the SI in WP5 demo) since they rely on the frequency measurement. They can still be complementary to grid forming. Indeed, grid forming ensures an instantaneous support to the grid but the duration of this support depends on parameters to be tuned and on the availability of energy on the DC side.

[D3.2] [D3.3]

Figure 13. EPFL demo results of the probability of the Relative Rate-of-Change of Frequency indicator in the case of grid forming and grid following. The proximity to zero highlights the positive impact on the Rate Of Change Of Frequency (ROCOF).

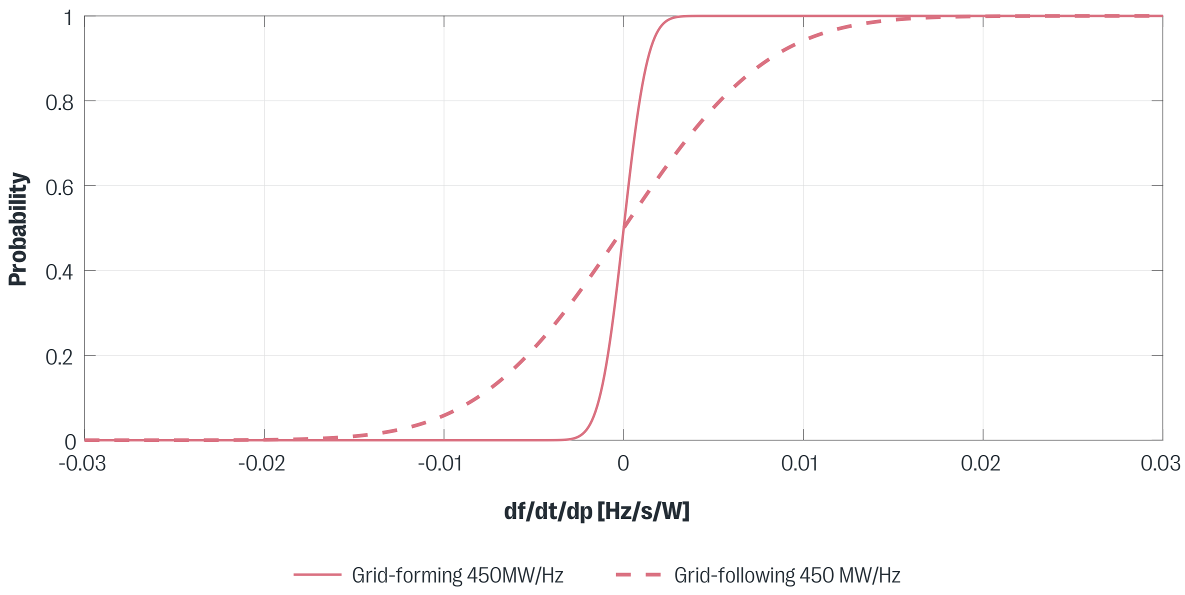
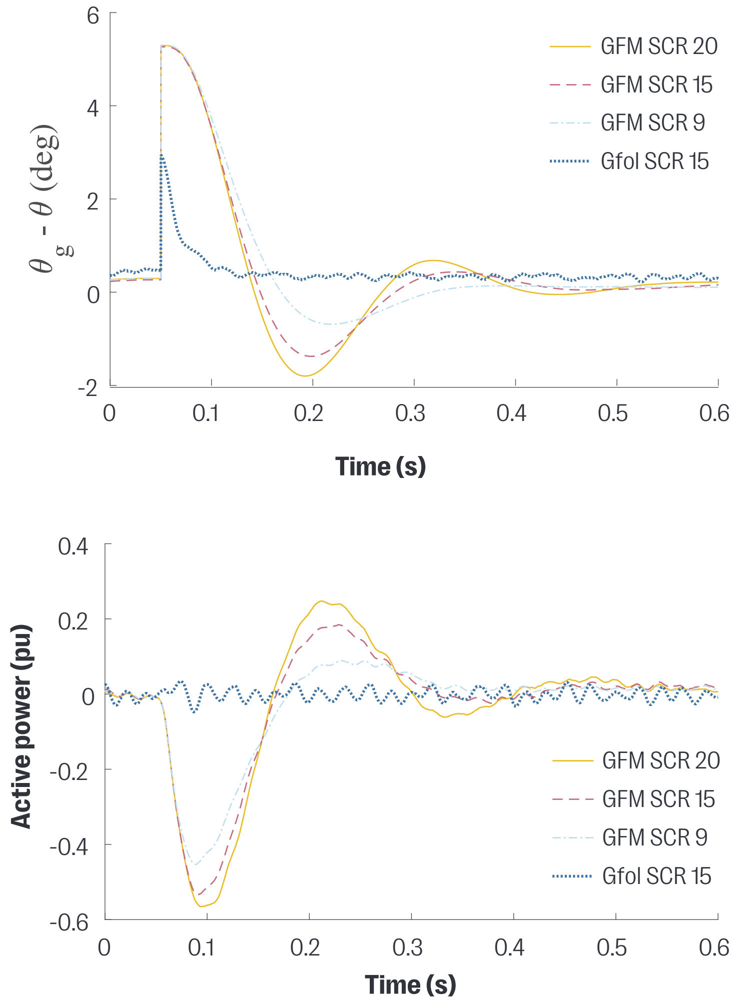


Figure 14. Ingeteam/RTE simulation validating the grid forming response (GFM) to a 5° phase jump in less than 5 ms for different short circuit ratio (SCR) versus grid following (Gfol).



Further R&D and regulatory evolutions are required for grid forming uptake

Many questions remain open to research in the field of grid-forming solutions, such as:

- The grid forming capability and testing of other technologies than BESS such as Variable Renewable Energy Sources (VRES), HVDC and FACTS without additional storage systems.
- The impact of grid forming controls on BESS ageing, but more generally on the primary source (within OSMOSE validation was performed only for Lithium Titanate battery and hybrid system with ultracapacitors).

- ✓ The system-wide and local needs for synchronisation services, their optimal deployment and scarcity risk analysis to define the best provision mechanism.

- ✓ The minimal energy buffer and current capability required to locally provide the required synchronisation services, depending on the system needs.

TSOs and regulators should now start anticipating the provision of synchronisation services in Continental Europe to avoid future scarcity in the system or high costs of retrofit of installations. Especially, WP3 recommends that minimal grid forming capability, within the installation capabilities, and the provision of synchronisation services should be made mandatory. Indeed, in that case, it will rely only on software updates as demonstrated in the project, without additional equipment. For instance:

- ✓ any BESS can become a "type 3 grid forming unit" without further capital cost until it is not expected to contribute to fault current beyond its rated value.

- ✓ a synchronous machine is by construction a type 4 grid forming. Unit sources with limited energy buffer can be certified as type 1 or 2 grid forming units and as such only provide standalone capability, fast fault current, system strength including or not synchronising power.

In any case, shared definitions and standard are crucial to limit the burden on industrial developments.

ⓘ **[D3.3] [16] [17] [18]**

2

Demonstrating RES and industrial loads flexibility

The increasing share of renewable and correlated decrease of synchronous generation share in European power systems lead to a paradigm shift in the way to manage system security and stability. While the flexibility of RES generators and industrial loads is clearly identified as a potential contributor to network security and stability, capturing it into real system services is still a technical, economic and regulatory challenge. OSMOSE demonstrated the technical feasibility of RES and industrial loads to provide ancillary services, paving the way to technical and legal requirements evolution and industrial developments. The close to real-time remaining flexibility of hydro generators was also investigated.

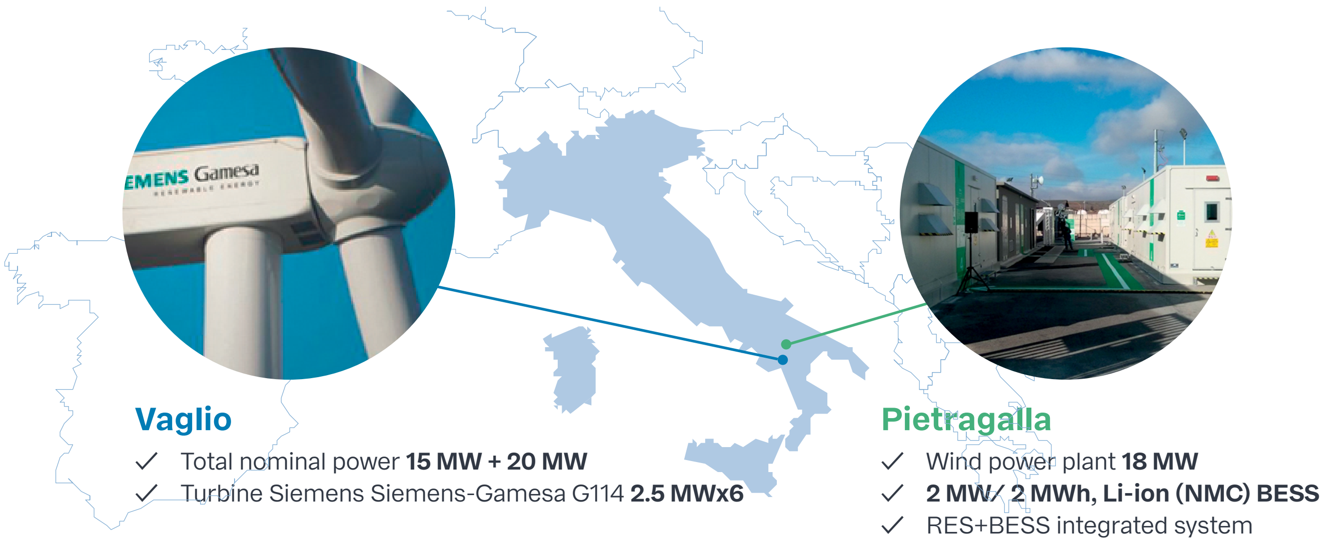
2.1 The provision of automatic voltage control and synthetic inertia by wind farms is demonstrated

At the time of the project start, in Italy, the participation to frequency and voltage regulation was restricted to plant above 10 MVA and with a programmable primary source, thus excluding wind, PV farms and industrial loads. The WP5 demo aimed to support the evolution of this regulatory framework by demonstrating and characterising their possible participation to ancillary services in the Italian context under the supervision of TERNA.

Wind power plants, with or without electrochemical storage, represent a valid resource for voltage regulation, with further improvements that can still be harvested in the future

WP5 demo led by TERNA investigated the provision of synthetic inertia (SI) and Automatic Voltage Control (AVC) by wind farms. Two sites were involved: the Pietragalla site owned by EGP, composed of an 18 MW wind power plant and a 2 MW/2 MWh BESS, and the Vaglio site with 35MW operated by E2i.

Figure 15. WP5 wind farms locations and technical features.



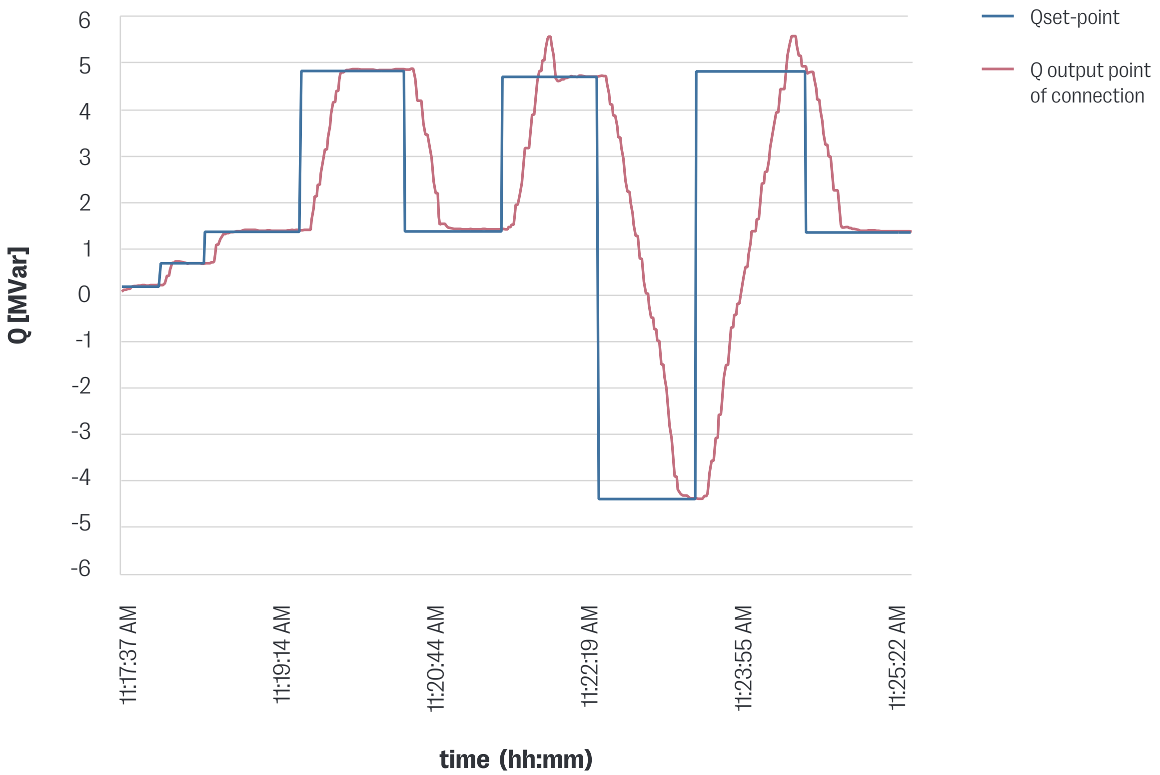
The two wind power plants' control systems were upgraded to allow for voltage regulation provision based on the new Italian Grid Code requirements, making the plants able to vary reactive power (Q) provision following a reference voltage or reactive power set-points sent by the TSO. In particular, a considerable amount of work has regarded the definition and implementation of the most appropriate list of set-points, signals, measurements and commands.

The experimentation showed that both a single wind power plant and an integrated wind and storage plant are technically capable of providing reactive power regulation, although they could not do it in the times requested by the Italian Grid Code, i.e. 5 seconds for the 100% Q provision. Actually, up to 40 – 60 s were needed for the largest Q variations with times increasing with the magnitude of the requested Q variation, as depicted in Figure 16. Coupling storage with such non-programmable resources has shown to improve their performance.

Part of the delays can be linked to the plants control system architecture that, although upgraded for the experimentation, has not been originally developed for this type of regulation. In this sense, the experimentation also allowed to identify improvements on the plants' control systems that could help reduce the times needed for service provision.

[D5.5] [D5.6] [1]

Figure 16. Example of reactive power (Q) set-point tests in Vaglio wind farm. The set-point is correctly reached but with a delay that needed further tuning of the controllers.



The provision of synthetic inertia within 500 ms was demonstrated for a wind power plant with electrochemical storage, its provision solely by wind farms would require additional work

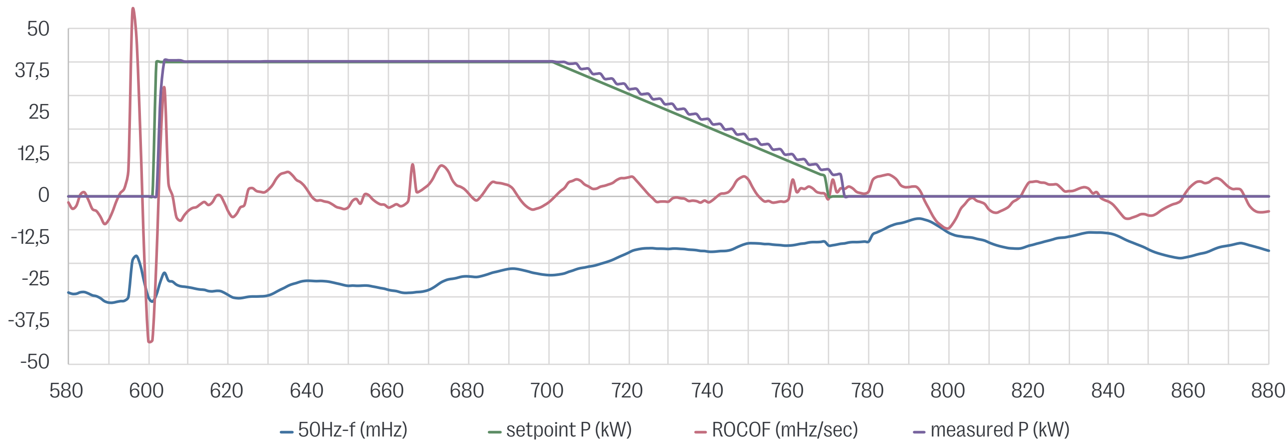
Synthetic inertia aims to inject/absorb power proportionally to the Rate of Change of Frequency (ROCOF), thus contributing to the limitation of frequency drops/peaks. This functionality becomes interesting when the whole system inertia decreases, due to the reduction of the numbers of synchronous generators (although this functionality cannot replace alone the inertia of synchronous generators, as further discussed in the section on grid forming).

In Pietragalla power plant, the Synthetic Inertia Control Device (SICD) was developed from scratch and installed onsite by EGP. The device collected measurements from the available HV transformers (with a 50 kHz sampling rate), calculated and filtered the frequency derivative (ROCOF) and sent the proportional active power set-point directly to the Power Conversion System (PCS).

The “measurement” module of the device constituted a challenge: the provision of SI needs to be almost instantaneous, but it highly depends on how fast the ROCOF can be calculated. Therefore, different calculation and filtering techniques were compared, and a polynomial fitting algorithm was finally selected: it allows parallel calculation of frequency and ROCOF by performing multiple derivation, starting from a polynomially-approximated angle phase function (taken at HV transformer). Further analysis determined the proper filter parameters to identify real frequency fluctuation events avoiding false positive due to electromechanical signal disturbances.

Test results showed a delay between event detection and power injection inferior to 500 ms, which is critical for an efficient support to frequency. The details of the response time are given in Figure 17. Notably, the SI response can be parameterised (ROCOF and frequency thresholds, droop, holding time, max/min power...). One of the most important areas to explore in the future is the correct identification of a “grid event” that requires the activation of the resource.

Figure 17. Timeline of the different signals implied in the SICD response to a frequency drop. The first 250 ms delay relates to the SICD’s performance, the following 150 ms depends on the Power Control System of the wind farm and the BESS and the measurement time of system performances.



Regarding SI experimentation on Vaglio-like wind turbines (i.e. without additional electrochemical storage), tests and analysis were carried on reduced scale and full scale test bench at Siemens Gamesa labs. The realization of such tests required the development of an upgraded firmware and software respectively on the converter on the wind turbine generator nacelle and on the control system of the wind turbine generator, following technical specification by Edison. These types of tests included real wind turbine components (Programmable Logic Control, Converter Control Unit, generator) and allowed to simulate the turbine power behaviour after the detection of a ROCOF event.

Simulations on turbine components showed that a 10% nominal power contribution, result of the use of the turbine inertia, can be safely provided by the turbine in a matter of seconds following a ROCOF detection and be held for times depending on the running active power. Field experimentation on a real turbine would be necessary to validate these findings, as well as further analyse lifetime impacts of such power insertions.

ⓘ **[D5.1] [D5.5] [D5.6].**

2.2 Industrial loads can technically provide ancillary services, however with significant hurdles

Five industrial sites in Southern Italy achieved to provide more than 100 MWh demand flexibility during the demo, however the required plants retrofitting revealed complex and the activable flexibility limited

Five industrial sites were tested to provide congestion management and "Automatic Voltage Control (AVC)" in a high voltage grid area between Apulia and Basilicata, Italy. The plants involved energy intensive processes (steel factory, foundry, oil refinery). Each of them underwent an energy audit and got the electric and telecommunication equipment installed by ABB to test and manage the flexibilities identified. The sites were managed by three Balance Service Providers (BSPs): Compendia, Edison and Enel X.

The equipment implementation on-site turned out to be a challenge, due to cybersecurity issues, radio interference with other factory equipment, but more generally to the heavy need for IT upgrade of the old sites (lack of connectivity infrastructures and automation devices). Also, the energy audits of the test sites showed that there was limited residual flexibility due to the optimisation of all industrial processes to maximise the industrial production and minimize the economic losses. The upgrade costs per site are given in Figure 18.

Figure 18. Overview of tests performed with industrial sites and upgrade costs.

BSP	Industrial plant	Service tested	Tested resources	Total cost of upgrade [k€]	Hours of testing	Energy provided [MWh]
COMPENDIA	Industrial Park	Congestion Resolution & AVC	Generator G5 Generator G6	99,7	132h45min	12,8
	Steel factory	Congestion Resolution	Blast Machine 1 Blast Machine 2 Decoring plant Compressor	23,3		
	Oil refinery	Congestion Resolution	Heating system	4,5		
EDISON	Powertrain industry	Congestion Resolution & aFRR	Cooling units (chillers)	9,8	99h	102
	Car manufacturer		Retired*	-		
ENEL X	Foundry	Congestion Resolution	Furnace	70	112h	0,73
	Military Site	AVC	Retired*	30,6		
-	Local Control Unit (all plants)			37,5		

*Two sites were audited but finally could not participate in the demo

Several days of tests were performed for each site, leading to the effective provision of the required services as summarised in Figure 18. Industrial sites proved to be reliable when it comes to slow services such as balancing and congestion management, considering the amount of energy extracted during the tests (about 114 MWh) and the high availability of the offers with respect to the TSO needs. A full real time test procedure with bidding and control from the aggregators was possible with some relevant upgrades to the site. The only technical open point remained the possibility to know the baseline of the single loads within each plant, given their small size with respect to the whole plant installed capacity. This can affect the controllability of the loads although they proved nevertheless reliable.

As regards AVC, local tests were performed in the industrial park to test the static and dynamic response of the implemented solutions. Tests consisted in the variation of the power factor reference of the generators (Medium Voltage level: 15 kV) to evaluate the voltage variations on the transmission grid. The main conclusion from the local tests was that, to enable this type of resources to the voltage regulation, it would be necessary to change the electrical arrangement of the plant and develop a logic of conversion of the set point (from V or Q to cos ϕ) so as to overcome the numerous constraints currently present and adapt the plant to the requirements imposed by Terna to ensure the grid resilience and stability.

Industrial sites that participated in the OSMOSE project will be able to use the equipment installed and tested in case of an opening of the Italian ancillary services market to such service provision.

ⓘ **[D5.5] [D5.6] [2].**

2.3 Short-term optimisation of bids unleashes flexibility for hydro generators

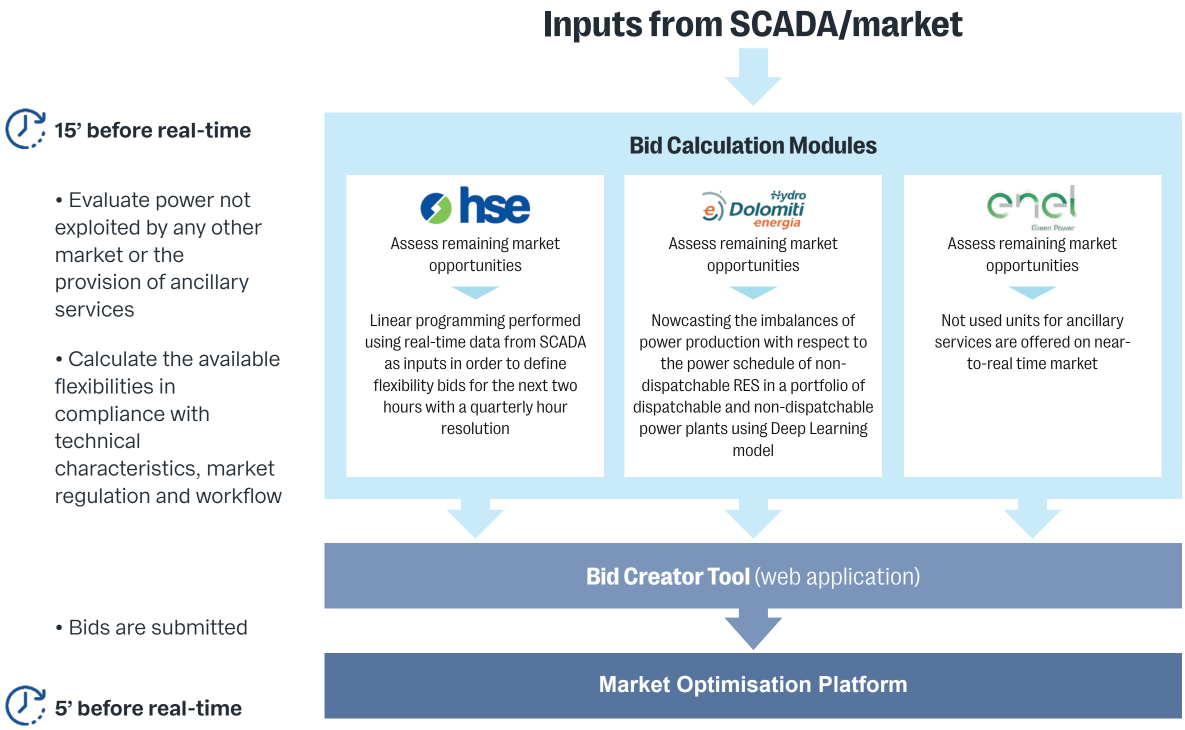
Hydroelectric producers aim to maximise the value of their assets: their production being subject to weather uncertainties, the potential imbalances between forecasted and actual generation lead to either charges, or loss of business opportunities. Such unbalances could however be turned into economic advantages if they can 1) be estimated precisely at the right time scale, and 2) be traded also after the closure of conventional markets (day-ahead, intraday, dispatching and balancing). For example, in Italy, the shortest-term market is the balancing market that accepts bids until 90 minutes before delivery time. The residual energy not reserved by the TSO for the Balancing Market could be offered on a dedicated flexibility market much closer to real-time.

Portfolio optimisation and nowcasting modules enabled RES generators to bid their close-to-real time remaining flexibility

In WP6 demo, tools were developed and tested with hydro generators HSE, HDE and ENEL, in Italy and Slovenia [Figure 19], to estimate their remaining flexibility 15 min before delivery time and send them as bids to a market platform [see section 3.1] for activation that occurs every 5 min. The principle of the tools developed are detailed in Figure 20.

Figure 19. Location of the plants involved in the WP6 demo.

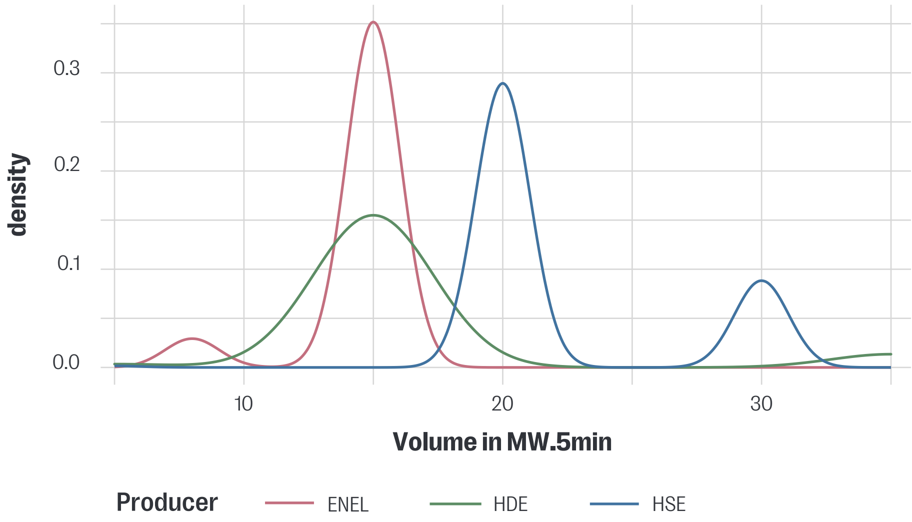
Figure 20. Functioning scheme of the Energy Management Platform.

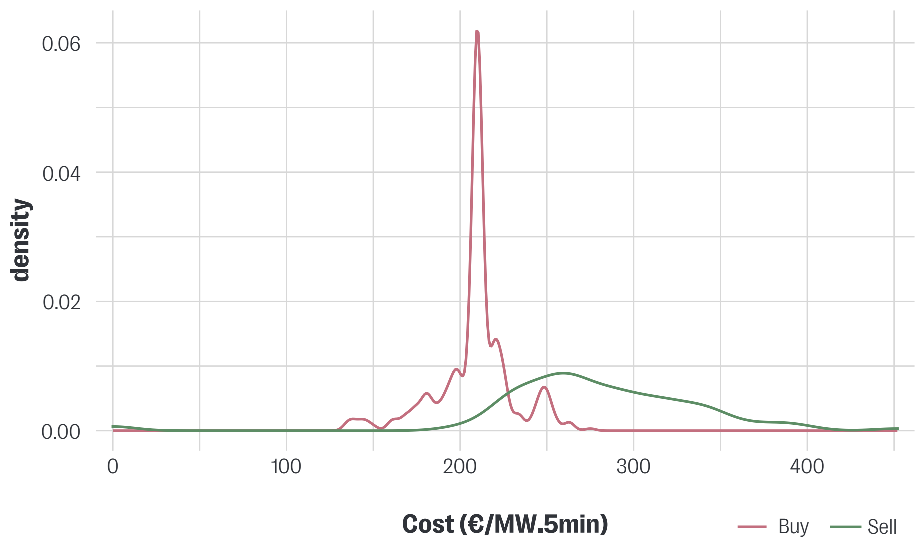


Real bidding sessions were performed during two weeks. Among the 1600 quarter hours tested, the maximum volume proposed downward (buying) was 35 MW and upward (selling) 20 MW, overall the volumes remained of course rather small. The maximum price proposed downward was 275 €/MW.5min and upward 451 €/MW.5min. Those prices were extremes and reflected the tension on the power market during the winter 2021-2022. [see Figure 21]

[D6.3] [D6.5]

Figure 21. Probability density of volume and prices offered by producers during two weeks of January 2022.





3

Demonstrating grid flexibility and efficient coordination

All flexibility levers are closely related, their optimal coordination should be facilitated and encouraged by the operational and market processes. The grid itself is a key flexibility lever and its optimal management brings significant value. The WP6 demo investigated how the consideration of grid constraints in close to real-time energy exchanges could create new secure business opportunities. In WP5, the flexibility of the grid thanks to innovative Dynamic Thermal Rating was demonstrated, and congestion management was enhanced by a new Energy Management System implemented on the TSO control room.

3.1 Close to real-time markets can create value without impacting system security when grid constraints are taken into account

As discussed in section 2.3, RES generation forecasts significantly improve close to real-time operation, and offering these adjustments to the market can have an interesting value. Regarding the grid, cross-border capacities are usually calculated two days in advance, when there are a lot of uncertainties, which force the TSO to take some margin on the calculations. On the contrary, in close-to-real time, most of the generation dispatch and the grid availability are known, which enables a precise estimation of the feasible flows. The WP6 demo intended to take advantage of these two elements: updated RES forecasts and grid availability close to real-time.

Close to real-time energy cross-border exchanges considering grid limitations was live demonstrated

WP6 partners – three TSOs (ELES, TERNA and RTE), three producers (ENEL, HSE and HDE) and three IT experts (EKC, Engineering and FBK) – together developed and live demonstrated the concept of a close-to-real-time joint optimisation of generation/storage/demand under grid constraints between Italy and Slovenia. This so-called “FlexEnergy Market” is a cross border energy market with a gate closure time 15 minutes before delivery time, a selection of bids every 5 minutes and a 10 seconds activation using the aFRR signal.

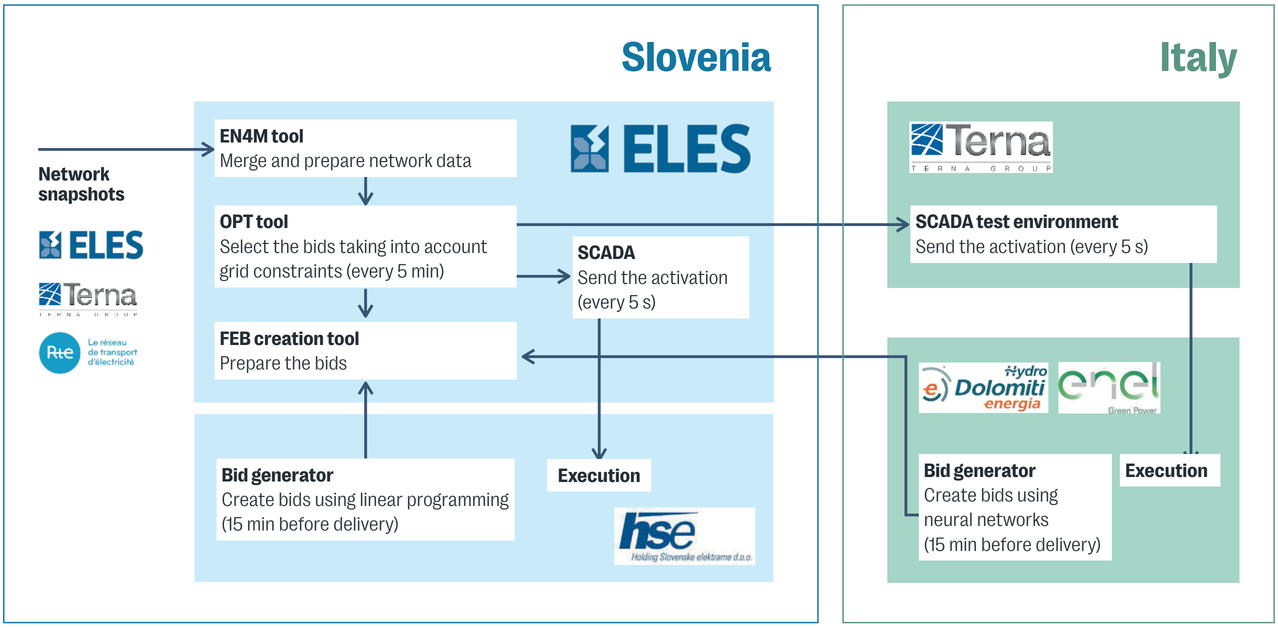
The whole process of bid offers, selection and activation had to be very fast, reliable and efficient and was a real IT challenge. The different steps of the process were the following:

- ✓ Creating flexibility providers bids [see section 2.3]
- ✓ Receive latest network data from grid operators and merge them in a single grid file. This step proved to be very challenging and time consuming in the process, advocating for the need of reference merged grid files shared between TSOs close to real-time.
- ✓ Receive the flexibility providers bids, pre-process them (quality check) and merge them in a single bid file

- ✓ Select the matching bids under security constraints. Security is a major challenge of such market: real-time exchanges should absolutely not create overloads on the grid as the TSOs will not have time to modify the dispatch. As a consequence, the algorithm to select bids ("OPT tool") takes into account the possible grid constraints in N and N-1 in the near future through an innovative security constrained Optimal Power Flow (OPF) using a Model Predictive Control (MPC) to simulate the future states of the grid.

- ✓ Activate the bids: the activation orders pass through the Supervisory Control and Data Acquisition (SCADA) of the TSOs and the aFRR signal for the purpose of the demo.

Figure 22. Tools and communication of the WP6 demo.



The demonstration was complex since it took place in the real business environment of TSOs and producers. For example, participating units had to be removed from standard trading environment with a notification of several days. The process also relied on real network snapshots created externally from the demo. Due to those limitations, only three real activation tests were conducted and led to effective cross-border activation on the 3rd March 2022. They demonstrated the feasibility of the process.

To further assess the market potential, the process was also run without real activation for two weeks. Only one match of offers occurred (5 MW during 10 min) due to the low liquidity of the demo market. During those parallel tests, exchanges were mostly limited by a gradient constraint of around 5 MW/5 minutes declared for some bids. On the contrary, network constraints were never limiting the exchanges, probably due to the small volumes at stake compared to transmission lines capacities.

Regarding computation time, the preparation of the network data took around two minutes and the optimisation of bids required less than two minutes in most cases.

Those durations were a good achievement but are not negligible since the target is to perform those steps every 5 min.

The scaling up of the WP6 demo is promising but also requires further investigations

The scalability of this WP demo should be further investigated by addressing the following questions:

- Market liquidity: due to the limited number of participants, this was of course an issue in the demo and the economic potential proved to be quite small. However, the penetration of renewables capacities, leading to more uncertainty in real-time, may increase the economic value of those markets in the coming decades.
- Scalability of the bid selection algorithm: the algorithm needs to run fast and to handle more bids, which will probably be more complex (like with temporal dependencies). The consideration of more grid flexibility (like topological actions or Dynamic Line rating) could also be a challenge.
- Market design: the demonstration focused on the technical feasibility but raises question of the market design to provide proper incentives and revenues to actors.

[D6.1] [D6.5] [D6.6]

3.2 Innovative tools for TSOs enable the grid to transmit more power and thus enhance its flexibility

To ensure the security of grid assets and people, the current transmitted by lines needs to be kept under specific ratings by Transmission System Operators. Innovative tools can enable a better assessment of these ratings dynamically. Together with local net load forecast, they can feed advanced Energy Management System in TSOs control room to better anticipate grid congestion and take the optimal preventive actions.

Innovative Dynamic Thermal Rating efficiently improves congestion management near real time

Historically, the current capacity of lines (Static Thermal Rating–STR) is estimated for typical weather conditions with some margin. In the last years, the concept of Dynamic Thermal Rating (DTR) emerged to maximise the flows on the line knowing precisely their capacity thanks to the estimated heat exchange behaviour of the line.

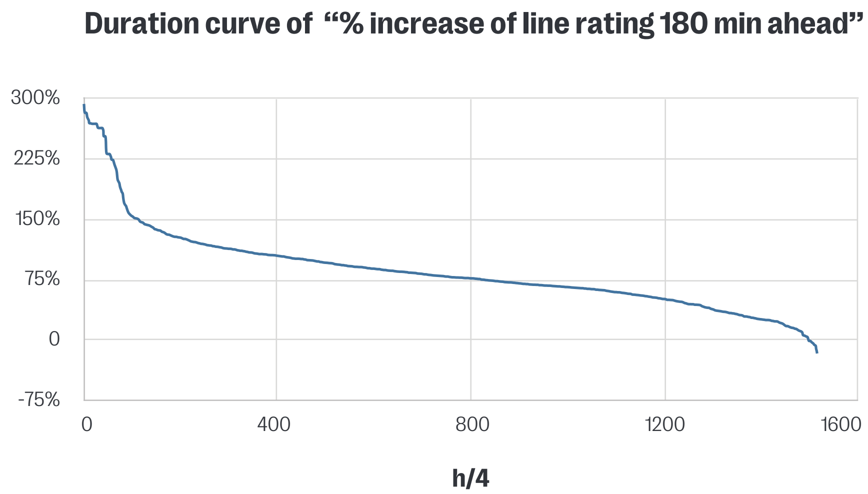
In WP5 demonstration, TERNA implemented and tested DTR on seven 150 kV backbone lines in southern Italy. The demo region was selected due to the frequent congestion experienced in case of high wind generation. Different DTR systems were installed:

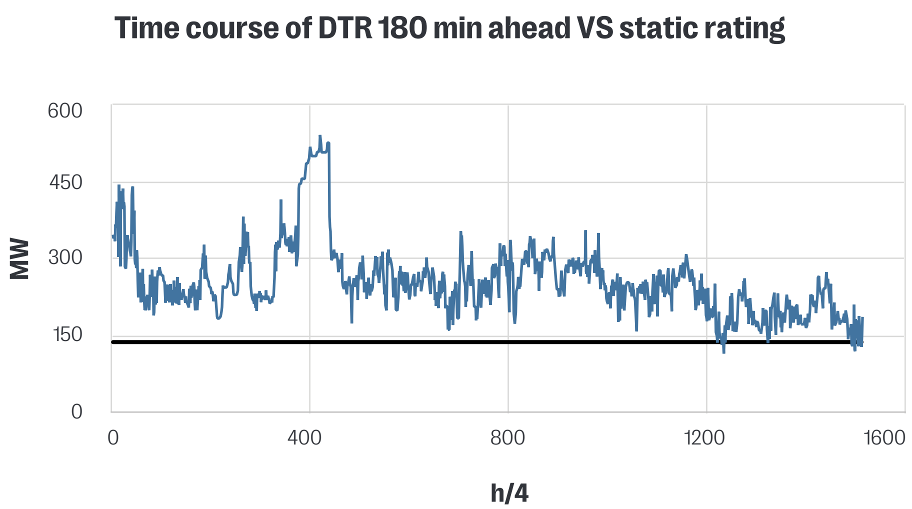
- Traditional DTR, based on the direct measure of conductor temperature on most critical spans and weather parameter monitoring, in order to estimate the conductor temperature trend and the maximum allowable current.
- Innovative DTR developed by ENSiEL, based on the deployment of cooperative sensors that communicate with surrounding elements in order to detect the hot-spot temperature and thus the current limit. This allows a decentralised measurement of conductor's temperature which does not require a central server to process local measurements from different nodes. The advantage of this solution is that the installation of the sensors is done on the line towers instead of on the conductors. It allows the TSO to save time, resources and to have a great number of DTR systems deployed along the electrical network.
- Weather based DTR using only meteorological forecast

Measures on 11 spans of 7 monitored lines during 8 months enabled to validate the effectiveness of the cooperative sensor network in assessing the conductor temperature. Each quarter of an hour, the weather conditions expected for the following 3 hours along the line path were forecasted. Starting from the present conductor's temperature, estimated span by span based on recent weather and loading conditions, the maximum current that could be sustained for the next 15 to 180 minutes was calculated.

Figure 23. Installation of DTR system on HV lines in the framework of the OSMOSE project.

Figure 24. Comparison between STR (black line) and 180min forecast DTR (blue line). for one line





The test campaign proved that exploiting short-term weather forecasting can at least double the steady-state thermal rating in 30% of the cases and even increase it up to 290%. Only in 1% of conditions, DTR is lower than STR, which is also a valuable information for the TSO. [Figure 24]

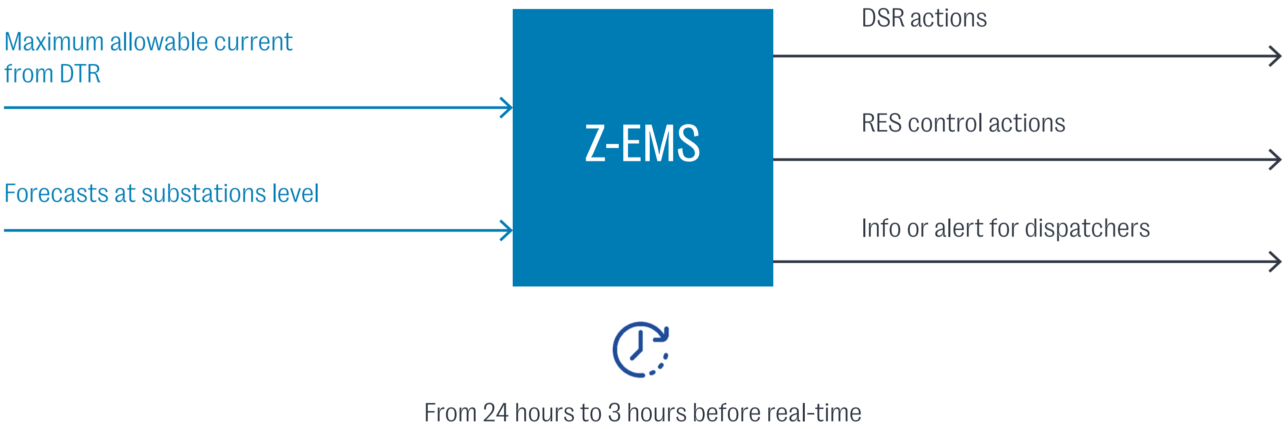
[D5.1] [D5.5] [D5.6] [9] [10].

Smart Energy Management Systems in TSO control rooms support advanced congestion management

Due to significant RES penetrations, congestions become more frequent in some grid areas. Their optimal management by the TSO is crucial to minimise curtailment while ensuring grid security. Advanced Energy Management Systems (EMS) in TSOs control room are very promising in that perspective.

In the WP5 demo, a new zonal EMS (Z-EMS) for South Italy was developed by IBM and installed in TERNA servers, working alongside its usual EMS. This Z-EMS is fed by DTR of lines (see above) and innovative forecast of consumption at substation level developed by RSE to increase the accuracy of congestion detection. The Z-EMS allows to manage congestions with a 3 hours ahead time horizon by proposing optimal actions to the operator.

Figure 25. Schematic operation of the Z-EMS.



The demonstration phase enabled to calculate various Key Performance Indicators of the Z-EMS. One out of two real congestions was predicted 1 hour ahead, one out of three was predicted 3 hours ahead. Some fake congestions were predicted too, but this might be explained by several reasons: Terna central EMS was meanwhile working to solve them; generation and load forecast had some uncertainties; these fake congestions were very small (tens of ampere). Possible improvements of the Z-EMS performances have been identified such as including reactive power forecast and topological changes.

[D5.5] [D5.6] [11]

3.3 The optimisation of distributed flexibilities can improve voltage grid control by DSOs

As distributed generation is increasingly connected to the distribution level, impacting system security, a systematic and closer TSO-DSO cooperation is required so the actions taken by one do not jeopardize the operation of the other.

An optimisation tool can improve the use of distributed flexibility by the DSO for voltage control in coordination with the TSO

The “Flexibility Scheduler” tool developed within WP7 by EFACEC, R&D Nester and REN aims at ensuring a given voltage at the TSO/DSO interface while minimising the grid losses for the DSO, by exploiting the flexibilities at the TSO/DSO interface and at distribution level. The tool performs a sequence-constrained OPF that indicates the optimised control of distributed flexibility resources: RES reactive power support, transformers' tap-changers position and shunt capacitors at both TSO and DSO levels. As a result, the tool provides to the system operator the flexibilities that should be activated as well as their set-points, for each hour for the next 24 hours.

16 test cases focusing on reactive power optimisation were simulated through Real-Time Power System Simulation (RTPSS) of a network model of the Portuguese transmission network, including both 400 kV and 220 kV lines, and 60 kV level (DSO level).

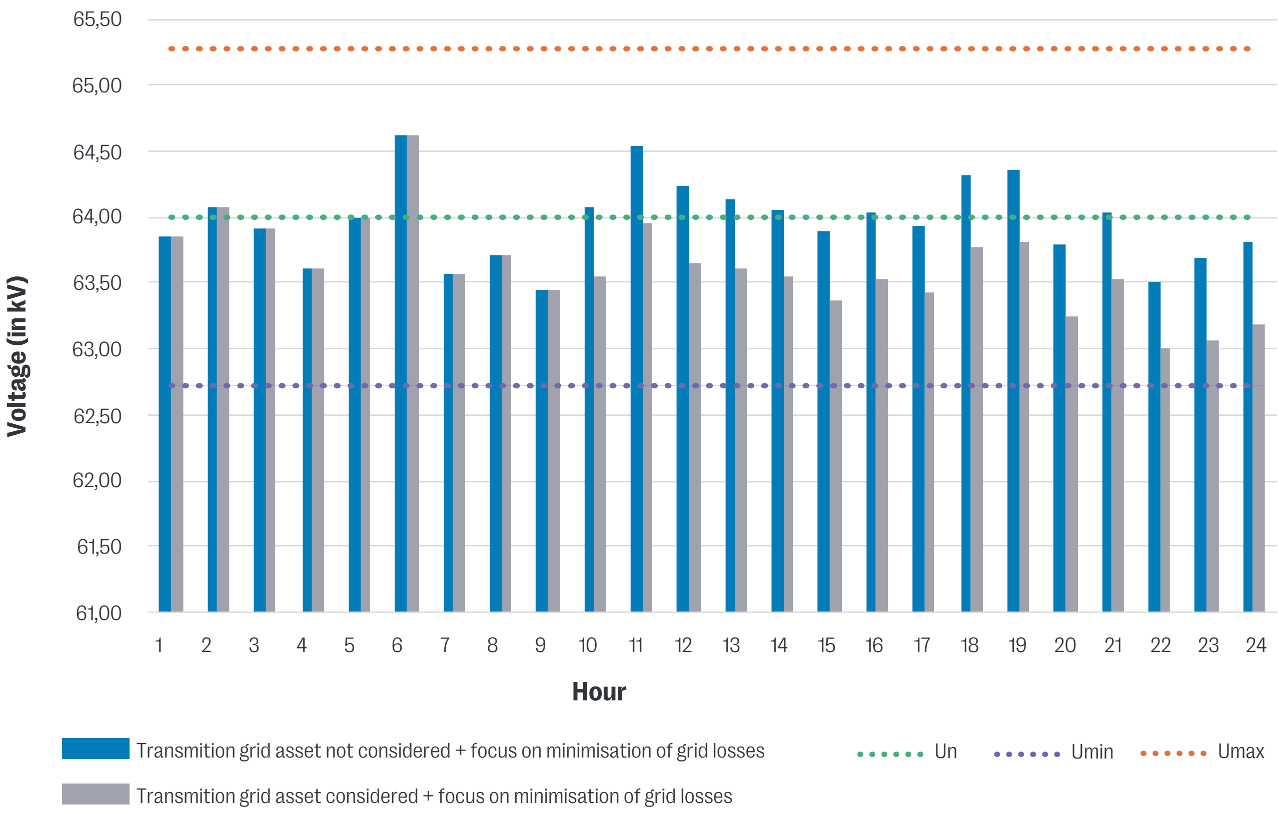
The solutions found by the Flexibility Scheduler included the reschedule of capacitor banks at both transmission and distribution substations as well as tap positions of distribution power transformers and generator's reactive power. The demonstration results showed that:

- ✓ All the operational plans generated by the Flexibility Scheduler resulted in maintaining all voltage levels within the acceptable limit of operation.
- ✓ The overall grid losses (TSO & DSO) were optimised: in average the reactive losses were reduced by 8.5 MVar and the reactive activation costs were reduced by one third.

The manufacturer EFACEC is planning the integration of the Flexibility Scheduler tool within its SCADA software suite [D7.4].

[D7.4]

Figure 26. Flexibility Scheduler voltage results for one of the substations interfacing TSO and DSO.



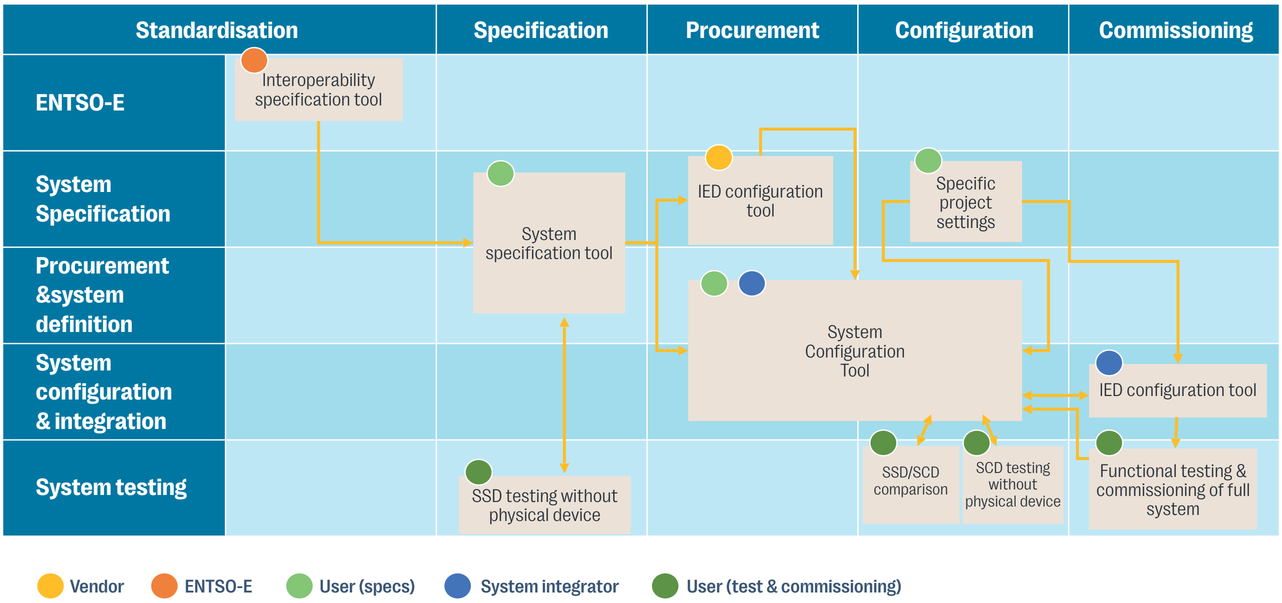
3.4 Standardisation eases flexibility deployment in substations

Interoperability is the ability of several devices possibly from different manufacturers to work together in a system, with the correct execution of its functions. In the last decades, the IEC 61850 standard was developed to allow interoperability in electrical substations and other power system facilities. However, the IEC 61850 standard failed to fully support a flexible and efficient engineering process from specification to configuration.

A standardised IEC 61850 engineering process simplifies the specification, procurement, configuration, and commissioning of substations for equipment vendors and system operators

In WP7, Elia, IT4Power, Schneider Electric and R&D Nester defined an optimised IEC 61850 engineering process, demonstrated by different specification and configuration tools. The enhanced process defines a way to go from a vendor independent system specification to an engineered and working electrical substation. It relies on the exchange of standardised machine-readable documents between the different project actors during the various steps of the engineering process (specification, procurement, configuration, commissioning). Those files are based on the IEC 61850 standardised System Configuration Language (SCL), making system requirements easily interpretable for vendors and the capabilities of Intelligent Electronic Devices transparent for System operators.

Figure 27. OSMOSE optimised IEC 61850 engineering process.



SSD: System Specification Description file **SCD:** Substation Configuration Description file **IED:** Intelligent Electronic Device

This extended engineering process was demonstrated at R&D Nester laboratory with devices and engineering tools from multiple manufacturers (Helinks, Schneider, Efacec, Ingeteam and Siemens) based on a use case and profile files provided by Elia. The full process was run from the initial specification down to the loading in devices and executing communication tests and simulation.

The configuration and simulation covered communication between substations to operate BESS, with IEC 61850 modelling done with Distributed Energy Resources (DER) functional model standardisedby IEC 61850-7-420 document. This exercise to model BESS with IEC 61850 was executed successfully, providing additional feedback to the IEC 61850 standard.

Many of this project's recommendations have been pushed to the IEC 61850 standard in the new document IEC 61850-6-100 which will be released during 2022. Next steps will be to implement this new standard document into IEC 61850 engineering tools and devices, and to promote IEC 61850 modelling for DER.

ⓘ **[D7.1] [D7.2] [D7.3].**

4

Modelling and quantifying future flexibility

Picturing the contribution of each technology in the future electricity mix is difficult, as many uncertainties exist on technological, social and political orientations. However, advanced quantified studies and simulations are crucial to support investment and market design decisions.

4.1 The flexibility needs and sources will evolve significantly between now and 2050 on all time scales

WP1 developed contrasted scenarios to question flexibility needs and sources from 2030 to 2050 in Europe, the full scenario data set having been made public

To analyse flexibility needs and sources in the future European power system, three contrasted scenarios were developed within WP1 by TUB using a capacity expansion tool which optimised investment in generation/storage/demand/grid from 2030 to 2050 with varying levels of CO_2 emission reduction. Although the results of such models should always be considered with care [see section 4.2], they provide interesting insights on future possible evolutions. The central scenario, fully compliant with the Paris Agreement, assumed a reduction of CO_2 emissions of 40% by 2030 and 80% by 2050 compared to the 1990 levels. Its security of supply level was assessed for 2030 and 2050 using the open-source hourly dispatch tool AntaresSimulator.

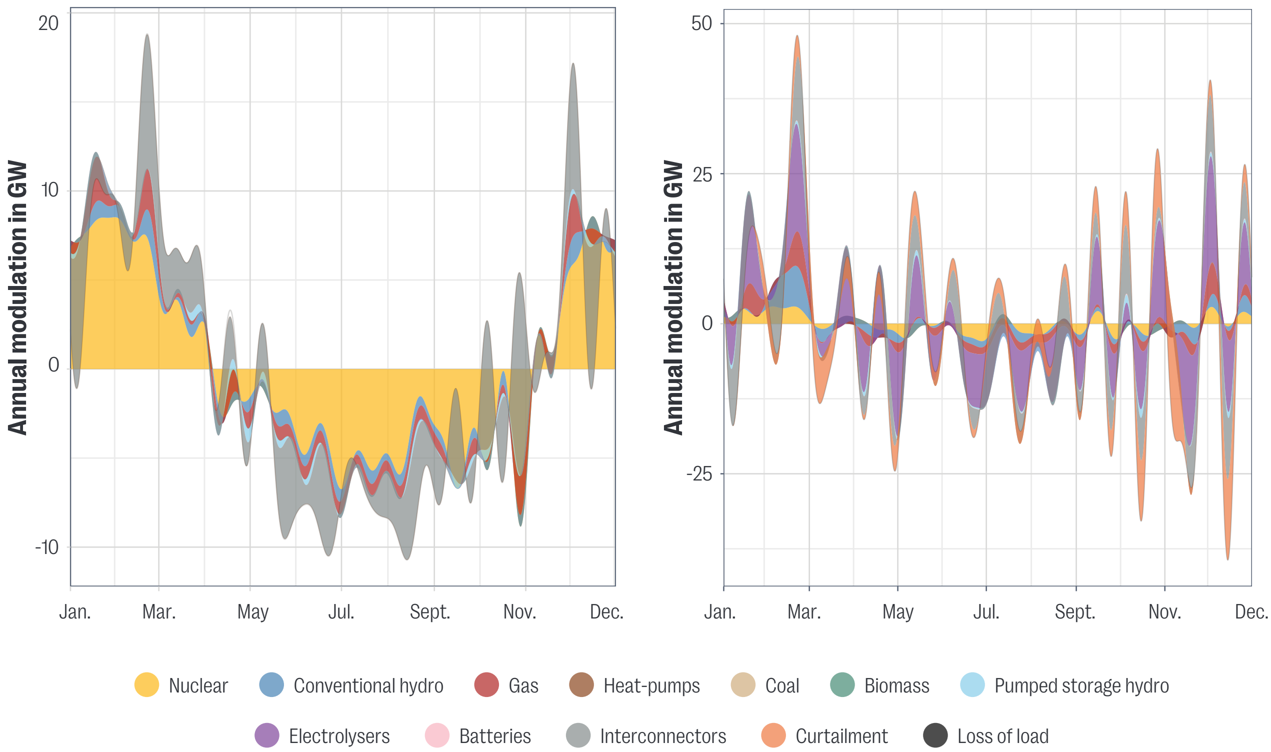
Data collection and model development represented more than 90% of the work and is a common barrier for such studies. To build upon this work and facilitate additional studies, the full data set developed by RTE, EKC and TUB is publicly available on the Zenodo platform. It includes the description of the generation, storage, demand and grid assets on a country level and on 99 more detailed zones for 2030 and 2050. 35 weather years of time series data (load and RES) are available, along with 10 years of forecast errors time series.

ⓘ **[D1.1] [D1.3]**

New metrics highlight the evolution of flexibility needs and sources on various time scales

WP1 was interested in establishing new metrics to address the question of who provides flexibility and how they actually interact together. From the frequency spectrum analysis of time series, indicators were created covering annual, weekly and daily time horizons. They were applied to the WP1 2030 and 2050 scenarios [see France in 2050 in Figure 28].

Figure 28. Contribution to the annual flexibility for one year in France in 2030 (left) and 2050 (right). This indicator captures the modulation of the flexibility solutions around their annual average value (note that y-axis scales are different).



In the considered scenarios, flexibility needs are notably higher in 2050 compared to 2030. A sensitivity analysis on France highlighted key trends regarding flexibility requirements. Whereas flexible power requirements are of the same order of magnitude for annual, weekly and daily timescales, regarding flexible energy requirements, the annual needs are greater than weekly and daily ones by one or two orders of magnitude. Notably, the daily flexibility requirements are highly dependent on solar penetration while the weekly ones are driven by wind penetration. Regarding the annual scale, the analysis shows a shift from a scheme where annual modulations are linked to consumption and generation maintenance patterns to a new scheme where annual modulations are linked to RES generation patterns which are irregular throughout the year.

Regarding flexibility sources, although the situation is country dependant, the following key points were highlighted in the considered scenarios:

- ✓ In 2030 and 2050, interconnectors remain one of the main sources of flexibility on all time scales.
- ✓ When there is a significant deployment of electrolysis, it becomes a major source of flexibility for all timescales (annual to hourly).
- ✓ In 2050, batteries provide significant flexibility but limited to the daily scale due to their limited energy rating.

- ✓ In 2050, gas turbines, ideally powered by green gas, are an important flexibility provider, especially in some countries like Germany.

- ✓ RES curtailment appears in 2050 on several timescales despite significant storage capacity and RES generation could be curtailed on a regular basis for up to several weeks in a row.

Interestingly, new cooperation schemes between storage solutions were identified in the simulations: short-term storages (batteries, hydro) were used to keep long-term storage (electrolysers) running outside sunny or windy hours, thus increasing their overall capacity factor and value to the system.

ⓘ **[D1.3] [8]**

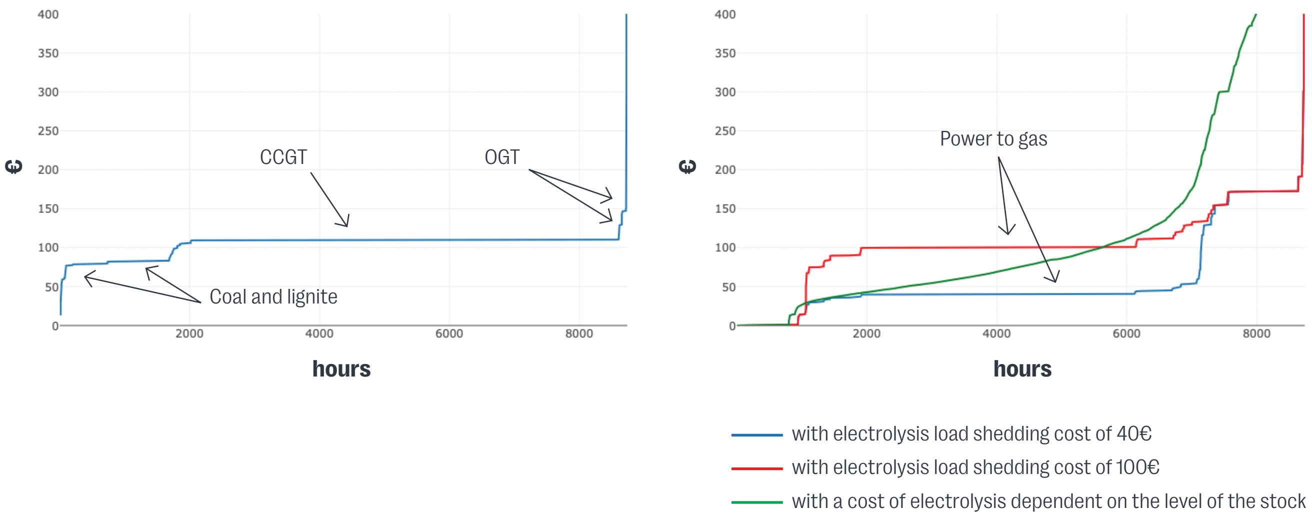
Electrolysers, if they become common in the future power system, could be a complete game changer for flexibility provision

The capacity expansion model used in WP1 to build scenarios suggested an investments of up to 420 GW in electrolysis in 2050 to achieve CO_2 emissions reduction. The hourly dispatch simulations showed that, if technically able to, electrolysers could become the major source of flexibility in the system in 2050. Indeed, their level of production reflects a trade-off between the cost of producing green gas and the value of this green gas, which in turn is linked to available storage capacities and green gas imports. In practice, this arbitrage tends to reduce the consumption of electrolysers in winter or during peak hours while gas generation from green gas contributes to satisfy peaks of net load.

The impact of electrolysers, and more broadly of flexible demand, on the system marginal price is also striking. In 2050, the power system being mostly powered via renewable energy sources whose marginal cost is zero, one could expect the marginal cost of the system to be often close to zero. The results actually showed that prices are then driven by demand, and in particular electrolysis, which sets the price around 75% of the year. The marginal cost is then very sensitive to the pricing strategy of electrolysers, which should be modelled with care in such scenarios. Different modelling approaches were tested in the project but should be further refined, notably to consider the effect of alternative import or generation of green gas. It is worth noting that zero marginal costs occur only for around 10% of hours in 2050 simulations (see Figure 29).

Figure 29. Marginal cost duration curves in 2030 (left) and 2050 (right with three different pricing strategies for electrolysers) in France.

[D1.3]



Reserves sizing needs to increase to follow RES penetration; improved coordination of energy, reserve and capacity allocation is essential to limit their future cost

A review of ENTSOE's current practice of automatic reserve sizing (FCR + aFRR) shows an affine link between reserve and installed wind and PV capacity (3% slope). This analysis allowed RTE and EKC to extrapolate the evolution of automatic reserve sizing to the 2030 and 2050 scenario. This leads to around 40 GW of reserves in 2030 for Europe and 90 GW in 2050. Despite this important increase in reserve requirements, in the studied scenarios, these reserves could be procured by various flexibility sources without increasing their installed capacity. Simulations also showed that this sizing was sufficient to properly address forecast errors, except for a few countries with high wind capacities but limited interconnections (United Kingdom, Ireland, Netherlands). However, the modelling assumed a co-optimisation of energy and reserve and an efficient use of interconnection for reserve procurement which are not currently operational in the current European market design.

REN, with its simulation tool PS-MORA, performed additional studies on the region of Portugal, Spain and France in 2030 and 2050. These showed that the long-term assessment of operational reserve requirements must model hydro capacity, not exclusively as demand peak shaving effects, but actually as flexible units ready to enter the system whenever needed while constrained by energy available.

[D1.3] [D1.4]

Simulations of the power system of Sicily in 2030 and 2050 show that dynamic system security can be ensured thanks to the participation of RES, BESS and demand flexibility

ENSiEL evaluated the impact of innovative flexibility sources (RES, BESS, Demand Side Management) on power system stability, by simulating some typical perturbations on the Italian island of Sicily. The grid model was updated to locally match the WP1 scenario for 2030 and 2050. For the 2030 time horizon, in most test cases, the studied power system was already stable without requiring additional flexibility options. Concerning the 2050 time horizon, the increased RES penetration pushed the system closer to its stability limits. However, the massive presence of new flexibility options such as flexible wind farms and FCR from demand response provided further control variables to support stability.

ⓘ **[D1.4]**

4.2 Capacity Expansion Models should be improved to better account for flexibility in future energy investment plans

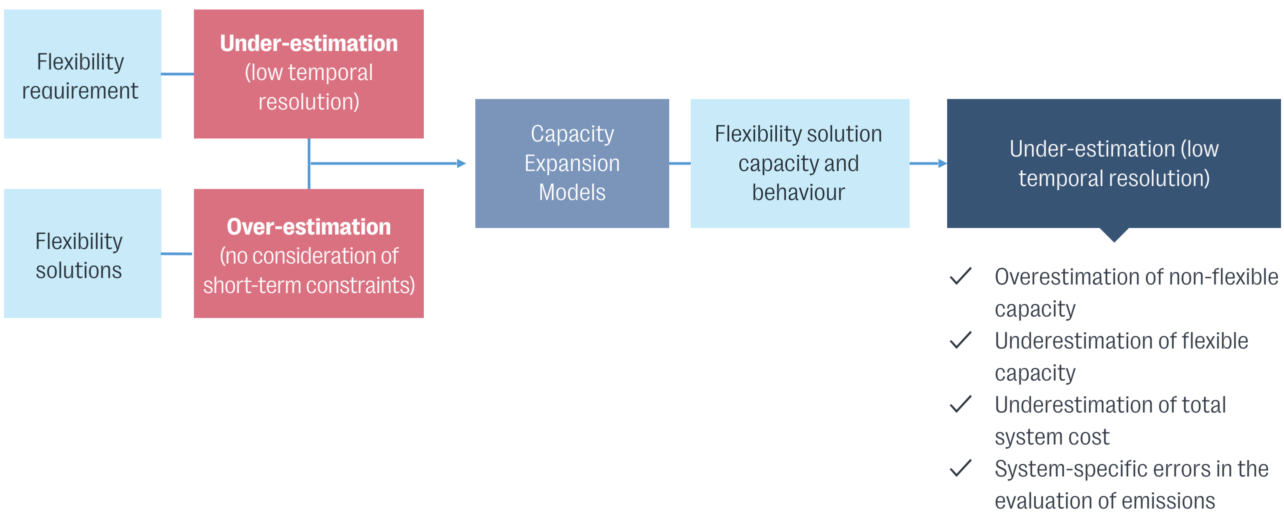
Capacity Expansion Models are key in power system planning and energy policy, as they provide the basis for stakeholders to decide when, where, how much and what technology type to build or retire. These models need to evolve to better capture the ongoing evolutions of the power system.

Capacity Expansion Models tend to underestimate the value of flexibility as well as CO_2 emissions; a more accurate representation of RES variability has a significant impact on the final investment plan

As Capacity Expansion Models cannot use hourly time series of load and renewable generation due to size and tractability issues, they typically use reduced time slices or series designed to capture variations in load and variable renewable energy generation. A typical modelling setup may use 24 time slices reflecting seasonal, intra-week and intra-day variations, thus offering a limited representation of variability and flexibility needs. Within WP1, RTE assessed the impact of different time slice structures and number on the model outcome. Results showed that improving the representation of solar and wind variability indeed impacts the final installed capacity.

[D1.3] [13]

Figure 30. Simplifications made in Capacity Expansion Model cause flexibility to be underevaluated. This leads to errors in optimal installed capacities, total system cost and emissions.



Industrial capacity and infrastructure development rate is a critical parameter to be considered in such models

RTE also explored the impact of the political and industrial capacity considerations on the Capacity Expansion Model outcomes, e.g. the ability of industry to develop onshore wind and solar generation capacity fast enough. Results show that industrial capacity constraints significantly impact the model outcomes. This conclusion highlights two points:

- ✓ the extent to which our ability to meet CO_2 emission reduction targets hold on industry's ability to roll-out new infrastructure fast enough, and
- ✓ the importance of taking this limiting factor into account in planning.

ⓘ **[D1.3] [13].**

Coupling Capacity Expansion Models with shorter-term production cost models allows to better account for flexibility in investment plans while complying with security of supply targets

One way to solve the issue of poor flexibility representation in capacity expansion models is to couple them with shorter-term production cost models, obtaining an investment strategy built upon a detailed consideration of operational costs.

RTE pursued this idea by coupling the capacity expansion model OSeMOSYS with the production cost model AntaresSimulator through a bi-directional soft linking framework [Figure 31]. The critical point in such a framework is the way information is fed back from the production cost model to the capacity expansion model to signal under- and over-investment and instruct how the investment pathway should be adjusted in the next iteration. Different feedback techniques were tested to ensure adequacy. Total system costs and generation mix proved to be significantly different with and without this soft linking [see Figure 32].

ⓘ **[13] [D1.3]**

Figure 31. Overview of the soft linking between capacity expansion model and production cost model.

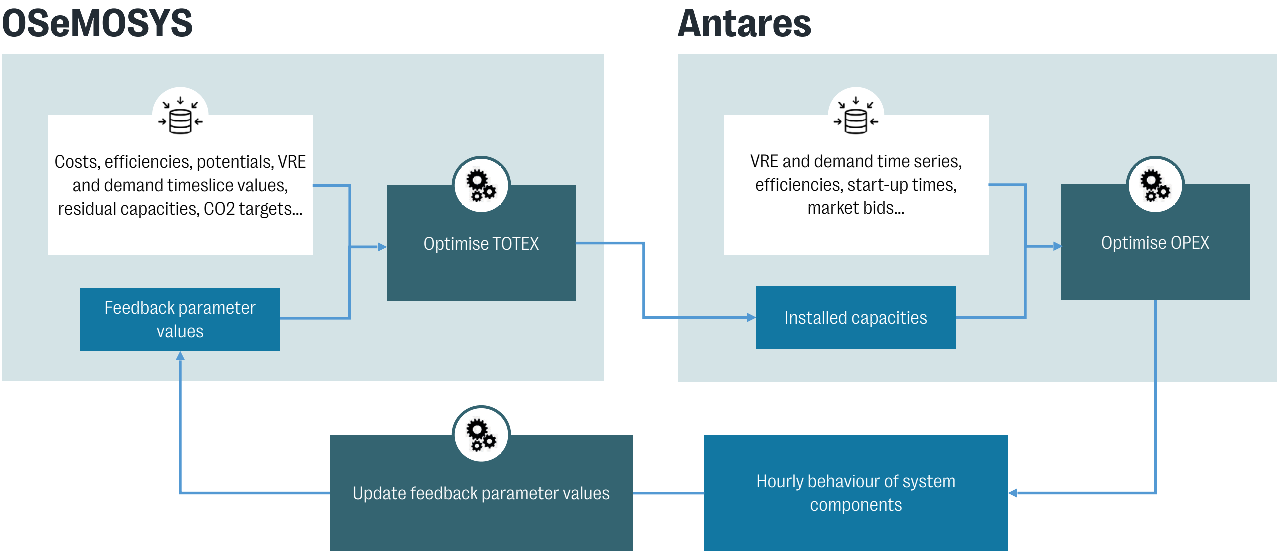
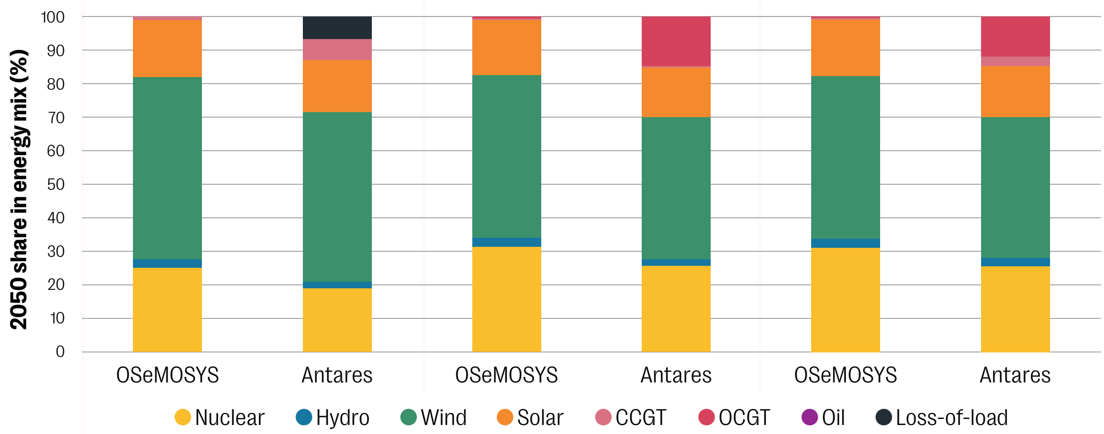


Figure 32. Comparison of a selection of OSeMOSYS and Antares outputs, for a uni-directional soft link (no feedback) and for the best adequate solutions proposed by two alternative feedback techniques.

		Uni-directional link	2nd feedback technique	3rd feedback technique
OSeMOSYS TOTEX (B€)		166	182	181
Antares LOLE* (h/y)	2020	3598	3	1,2
	2050	1964	2,45	0,7



Emissions (Mt/y)	2020	153	123	130	127	146	133
	2050	1,6	16,5	1,9	53	1,4	49

*Loss Of Load Expectation

Considering sector coupling in Capacity Expansion Models is key but requires novel adaptations to maintain computational tractability

In addition to the modelling approach described above, consisting in soft-linking the investment planning and the dispatch stages, TUB explored in WP1 how modelling techniques can be improved to integrate both steps. As well as guaranteeing consistency and optimality, this approach can identify synergies in the provision of flexibility across the entire energy system, for instance, how residential heat storage might be an efficient solution to substitute peak-load power plants.

This led to the development of the AnyMOD.jl modelling framework to model large energy systems at a high space-time resolution, accounting for sector coupling and high RES shares. Therefore, the framework can be considered a synthesis of 1) capacity expansion frameworks with low detail but a comprehensive sectorial scope and 2) frameworks with great detail but a focus on the power sector.

AnyMOD.jl introduces a graph-based approach, where each set (time-steps, regions, energy carriers, and technologies) is organised in a hierarchical tree. This enables two key features:

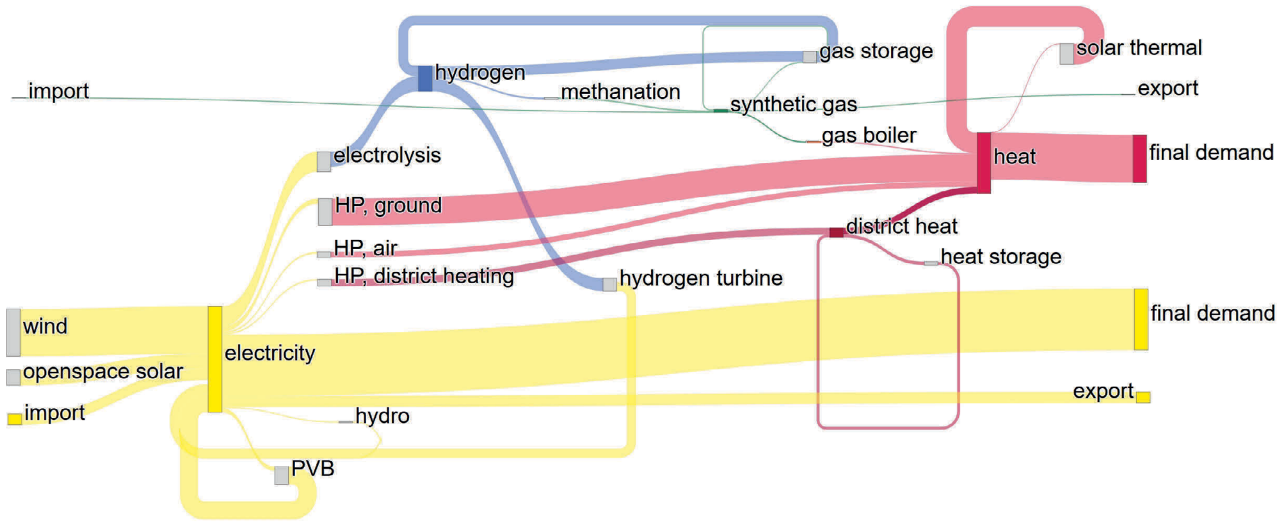
- ✓ The level of temporal and spatial detail can be adjusted by energy carrier, providing the model with a high level of detail and a large scope, while keeping models computationally tractable. At the same time, specifically adjusting the temporal resolution can capture the inherent flexibility within certain parts of the energy system. For instance, modelling gaseous energy carriers at a daily resolution while using an hourly resolution for electricity does not only reduce computational complexity, but implicitly also captures the storage capacity of the gas grid.

- ✓ The degree to which energy carriers are substitutable when converted, stored, transported, or consumed can be modelled to achieve a detailed but flexible representation of sector integration. For instance, the approach captures how gas turbines can run on both natural and synthetic methane, two carriers that come from very different sources.

AnyMOD.jl is implemented as an open-source tool in the Julia language. In a test case, compared to a different modelling framework, a model created with AnyMOD.jl was solved five times faster but leading to the very same results. The model is suitable for use by companies, regulators, or non-governmental organizations and has already been successfully applied in several peer-reviewed publications and policy papers.

ⓘ **[D1.4] [14]**

Figure 33. Exemplary Sankey diagram resulting from AnyMod.jl.



4.3 Modelling market operation is essential to make quantified assessments of their performance, but is complex and remains a challenge

Market designs should facilitate the realisation of an optimal electricity market dispatch through adequate opportunities and remuneration of actors. While current market designs are challenged by the evolution of the power system, market evolutions are commonly suggested with a lack of quantified assessment of their benefits in realistic power systems.

Modelling of RES forecast errors paths at different look-ahead times is required to feed into market simulations

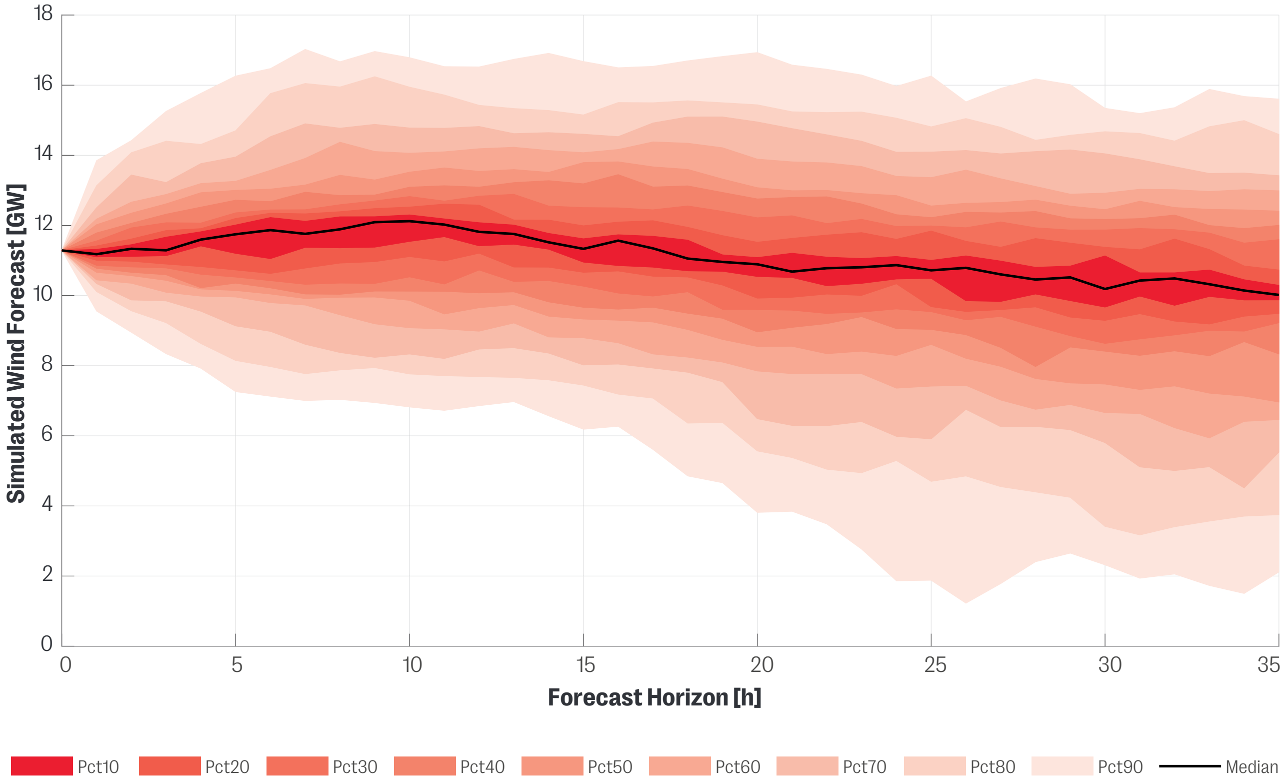
A key stake for market design modelling is the proper integration of forecast errors which create needs for short-term flexibility and which go beyond the assumption of perfect foresight of actors. Appropriate forecasts modelling is thus a prerequisite to simulate and assess the capability of different market designs to provide adequate incentives for flexibilities.

WP2 proposed a new methodology based on historical forecast updates applicable for various look-ahead times and reflecting the different fundamental characteristics of wind, solar and load. Forecast paths were modelled in a multivariate formulation of the corresponding distribution function, usually implemented using a copula-approach. This methodology developed by UDE and RTE was trained using RTE's 2016 forecasts and supplied the 2030 market simulations performed by RTE and UDE. The impact of forecast errors on market outcomes proved to be significant as further discussed in section 4.4.

The methodology could be improved in future works, for example by taking into account the impact of higher installed capacities on forecast errors in the future system.

ⓘ **[D2.1]**

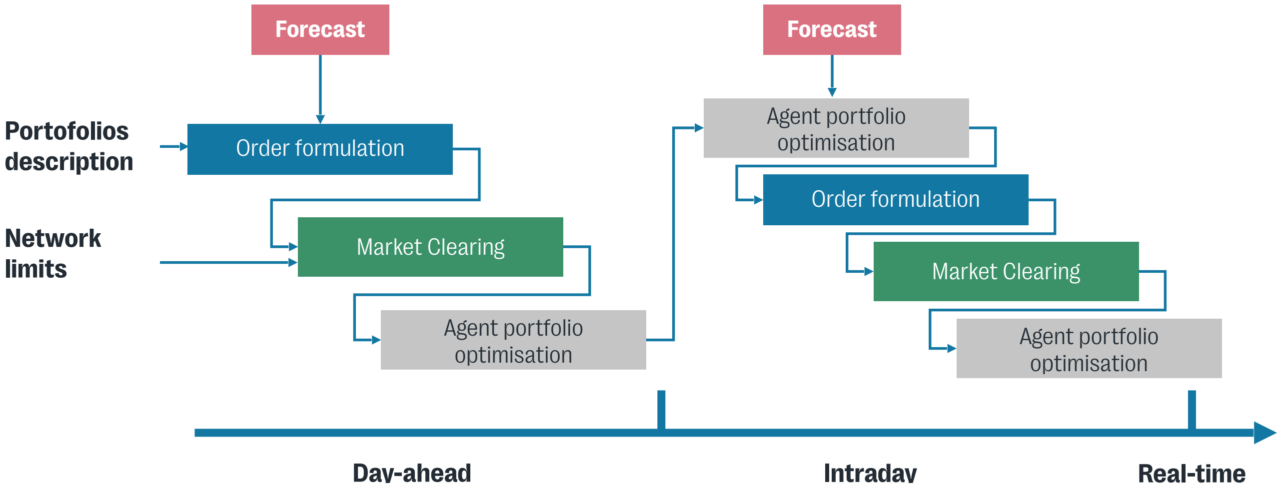
Figure 34. Development of the percentiles of 200 forecast paths for a single delivery period plotted against the forecast horizon.



An agent-based market modelling allows improved representation of uncertain information, technical constraints and actors' strategies

As market participants get closer to real-time, they are exposed to uncertain information of which the precision is gradually improved over time. As this information gets revealed, they adapt their planning and infer the orders they should submit to subsequent energy markets. These orders are collected and cleared by market modules, while agents are given several opportunities to redefine the way their market engagements can be met using their asset portfolio. In order to simulate this process, the ATLAS model (for Agent-based short-Term eLectricity mArkets Simulation) developed by RTE was used in WP2 to simulate a sequence of electricity markets represented in a series of steps involving different modules [see Figure 35].

Figure 35. ATLAS process modelling day-ahead and intraday market processes.

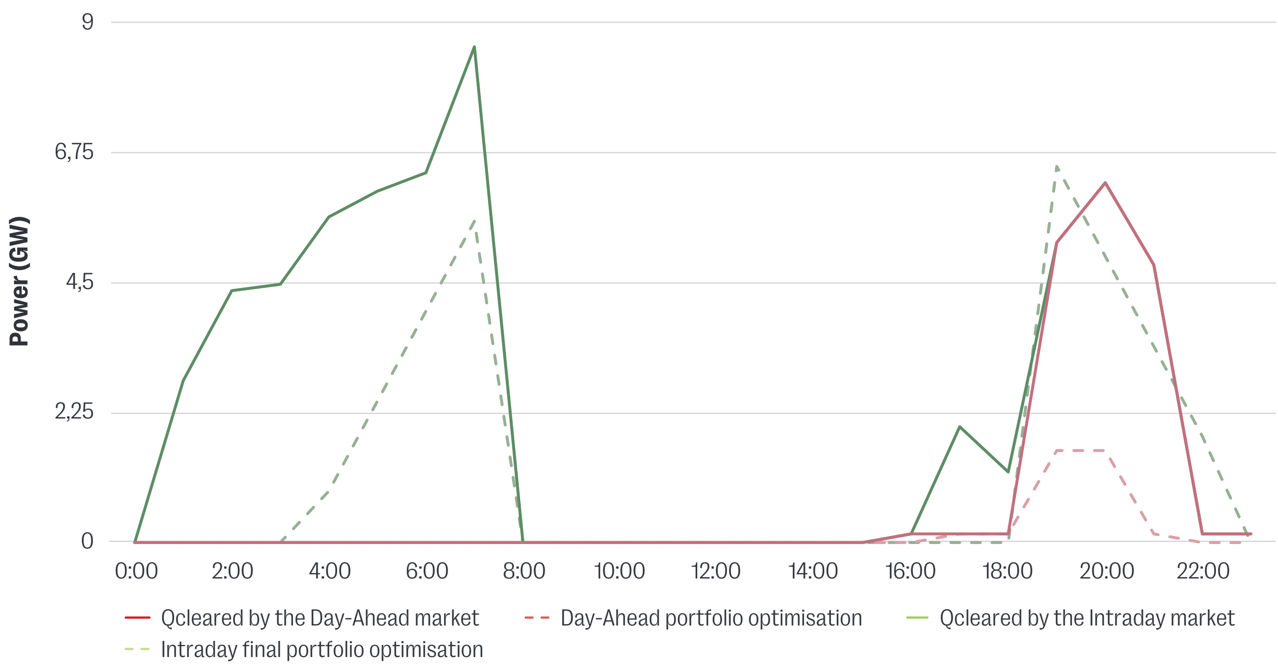


The main advantages of the approach are its modularity and its ability to represent complex but realistic behaviours and constraints that are close to those experienced by generators, TSOs and consumers in real life. However, the development and interfacing of the required model components is extremely challenging and the sophistication of the simulation induces high computation times.

The ATLAS model was successfully applied by RTE for its WP2 study [see section 4.4], showing that the simulation of the different market steps impacts the final dispatch and is hence crucial to understanding the details of short-term power system operation.

[D2.3] [D2.4]

Figure 36. Example evolution of Spanish CCGT dispatch over ATLAS steps.



Modelling the distribution network using representative networks allows for prospective simulations thanks to open data

Since a significant part of future flexibility will be connected at the distribution level, its modelling in prospective and market design studies becomes critical. However, a lack of grid data is usually experienced by stakeholders. To address this issue, in WP2, EnSiEL developed a methodology to build representative distribution grid networks behind primary substations. These synthetic networks are constituted by a combination of elementary portions of networks, representative of given ambits (i.e., urban, rural and industrial feeder, shown in Figure 37) according to open geographical data such as demography, land cover and usage or number of buildings.

The methodology was applied to 263 primary substations of central France to assess the availability of flexibility products and their costs to be offered to the ancillary services market by DER in a 2030 scenario. The results demonstrated that the grid limitations of the distribution networks cannot be disregarded. It also highlighted the benefits of the developed tools to estimate the impact of the provision of some flexibility products by DERs, if procured in market sessions [see Figure 38].

[D2.3] [D2.4] [15]

Figure 37. Elementary portions of network used for building the model of real DNs.

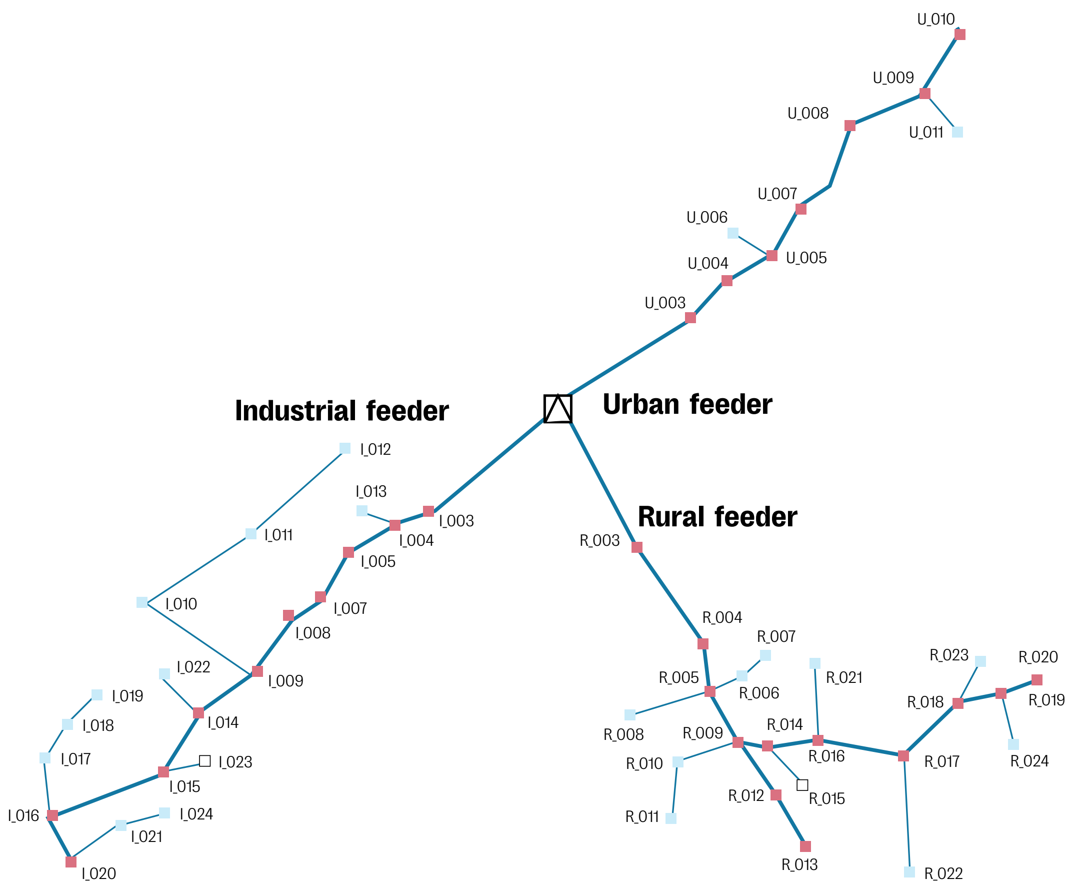
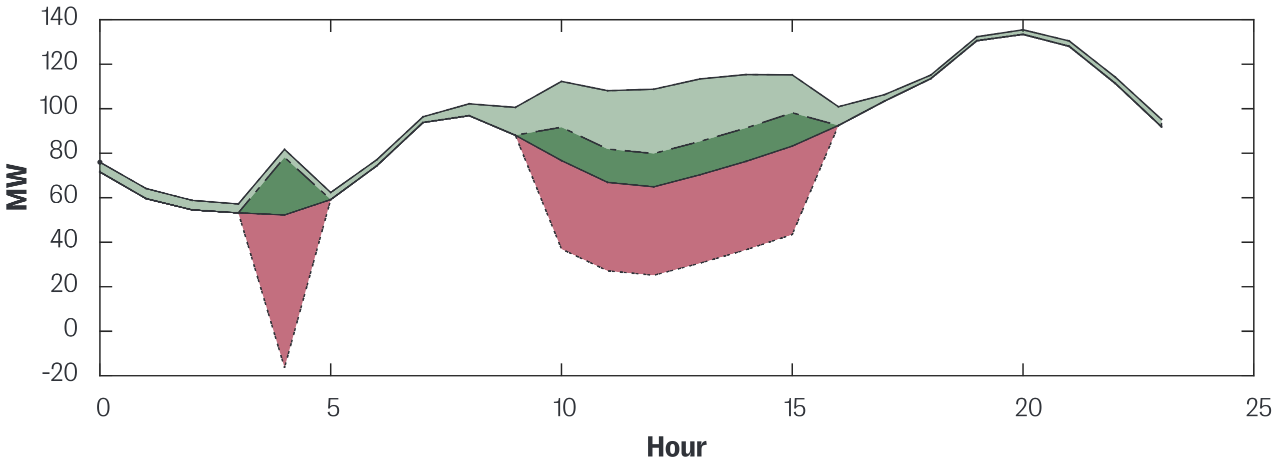


Figure 38. Example of a residual flexibility profile at the TSO/DSO interface (light green: additional downward feasible bids, deep green: additional upward feasible bids, red: unfeasible quantity due to bottlenecks in distribution networks).



European scale zonal and nodal market simulations were performed but significant challenges remain for quantified market design analysis

Within WP2, UDE and RTE performed large scale market simulations with their own frameworks that complement each other in terms of functionalities and use cases. Notably, UDE developed a version of its Joint Market Model (JMM) that enabled a year-long simulation of the operation of generation units and flexibilities as well as the corresponding power flows in the European grid at a nodal level for seven countries in 2030. Such advanced studies are necessary to identify complex system behaviours which cannot be seen in simplified test cases. However, although achievements in modelling were reached, the following points turned out to be still very challenging:

- ✓ The availability of consistent grid and geographical data at European scale in future scenarios
- ✓ The adequate precision of modelling of grid constraints and flexibility
- ✓ The computation time and expertise required for such complex models

[D2.5]

4.4 The role of intraday markets and local flexibility will be strengthened by increasing RES penetration and the emergence of new flexibility providers by 2030

RTE and UDE applied their respective models on a WP1 scenario to simulate the day-ahead and intraday energy markets in 2030 for Europe. In the case of RTE, the analysis was limited to a single day due to its complexity. In the case of UDE, the lack of adequate grid data limited the relevance of the observed grid constraints. In both cases, the results should thus be interpreted with care although some interesting phenomena were still identified.

Dispatch and prices variability between day-ahead and intraday markets will increase with RES forecast errors

With current forecasting methods, the error in RES forecasts only decreases significantly 3 hours before real-time. With the increasing share of renewable, this means the dispatches resulting from the day-ahead market and the intraday sessions are expected to diverge more and more in the future. On top of this effect, market dispatch differences also appear due to the decisions agents must make over the market sequence. For example, in one of the simulations performed by RTE, the net load over the whole day and the whole of Europe only changed by 13 GWh (0.02%) between the day-ahead and the intraday forecasts. However, some flexibility solutions in specific countries adjusted their behaviour by 39 GWh (thermal in Spain), and some countries' net positions changed by as much as 93 GWh (United Kingdom). As a consequence, the simulations also highlighted significant differences in price ranges between those markets. The yearlong simulation performed by UDE brought a broader understanding of the contribution of various flexibility sources in addressing forecast errors between day-ahead and intraday [see Figure 39].

ⓘ **[D2.4]**

Figure 39. Impact of forecast updates on production over one year of the 2030 simulation performed by UDE.

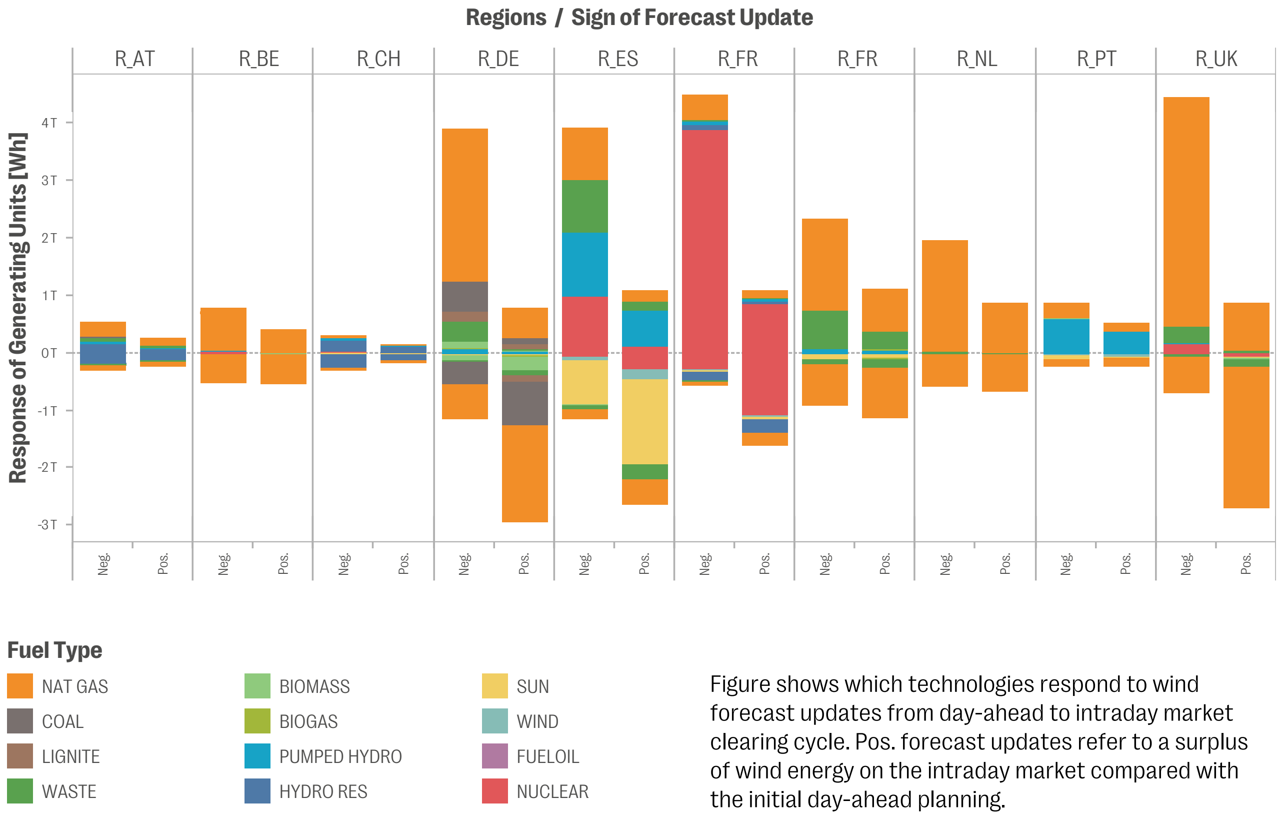


Figure shows which technologies respond to wind forecast updates from day-ahead to intraday market clearing cycle. Pos. forecast updates refer to a surplus of wind energy on the intraday market compared with the initial day-ahead planning.

Grid congestions and flows will become harder to anticipate in day-ahead and interconnections will contribute significantly to intraday flexibility

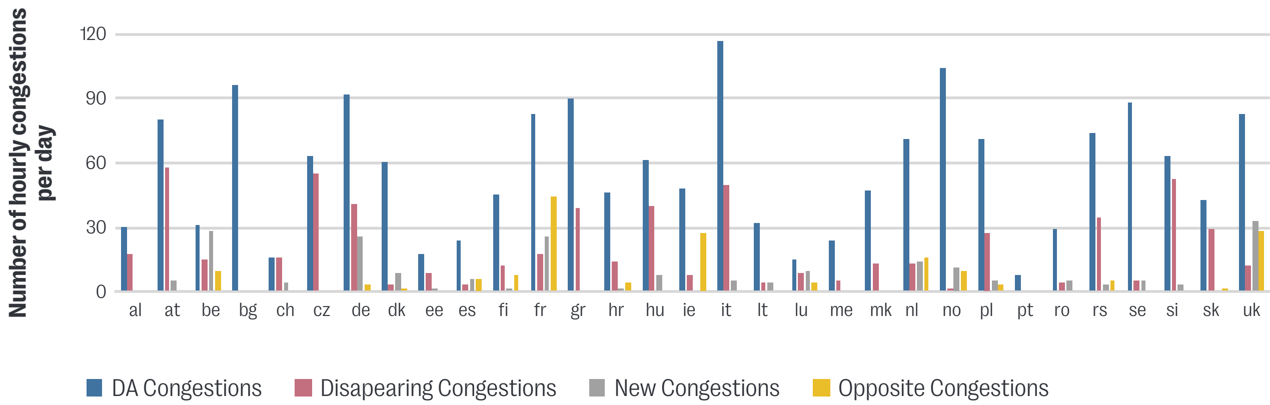
Simulations showed that interconnectors are a much called upon solution to adjust between market sessions, and that day-ahead markets make a poor assessment of intraday power flows. For example, in one day simulated by RTE, out of 1700 cross border congestions foreseen in day ahead markets, 35% were alleviated in intraday, 10% occurred but with a reverse direction of power flows and an additional 12% of unforeseen congestions appeared in intraday [Figure 40]. The yearlong simulation performed by UDE highlighted especially that small countries with high storage capacity like Austria or Switzerland provide significant support to their neighbours in addressing RES forecast errors.

As a result, TSOs coordination around cross border capacity will become critical and should be improved. This applies for both capacity calculation and allocation (particularly on the intraday), but also for congestion management. The consideration of uncertainties in capacity calculation and allocation appears to be critical. Ongoing work at RTE are for example addressing the possibility of taking uncertainties into account in flow-based calculations. This also points to a likely drawback of day-ahead nodal markets with increasing RES penetration: the prices sent to the market participants could be more and more misleading.

For long-term studies, these results also highlight the importance of the modelling of cross-border capacity calculation and the impact of uncertainty.

ⓘ **[D2.4]**

Figure 40. Cross border congestions evolution between Day-ahead forecast and intraday update, aggregated by country.



Increasing real-time grid congestion with RES penetration calls for a smart local use of flexibility

The impact of local grid constraints on flexibility needs and solutions was studied in different OSMOSE tasks.

First, EKC performed 2030 and 2050 dispatch simulations with a resolution of 99 zones for Europe. This geographical down-scaling led to different results from the country scale simulations mostly due to internal grid constraints. Further analysis would be required to assess whether the optimal solution for mitigating this congestion is re-dispatch, which can represent an additional revenue stream for flexible units, or if this rather calls for more internal grid developments.

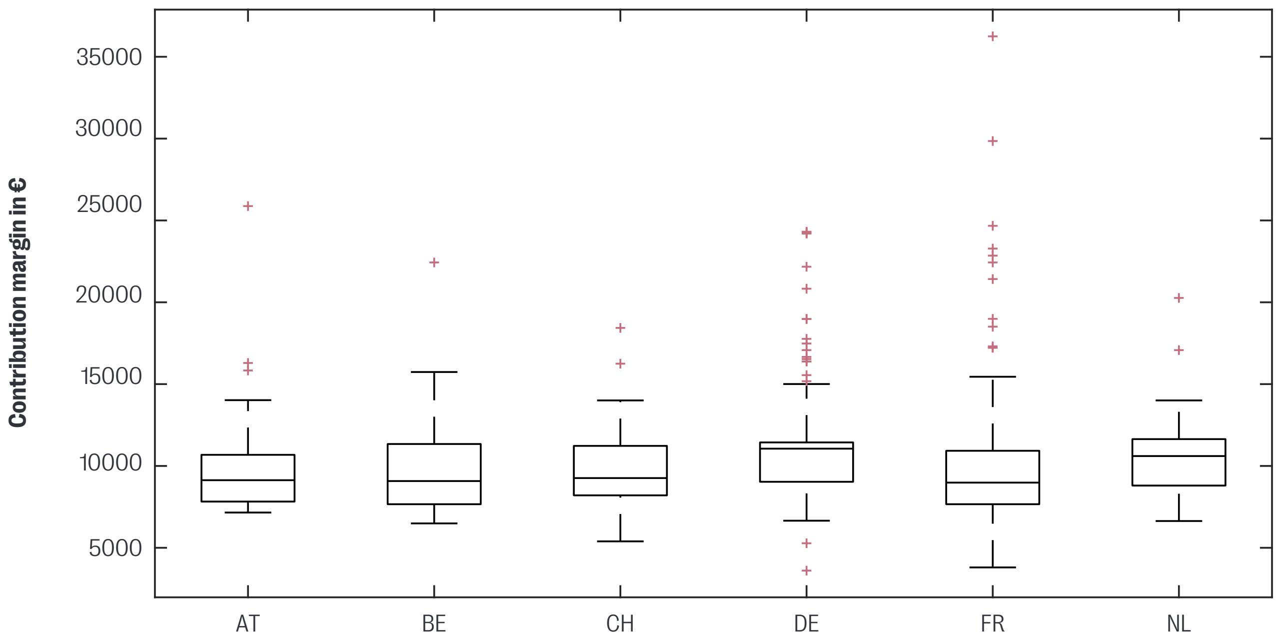
In addition, R&D NESTER made an analysis focused on the identification and resolution of potential network congestions in the Portuguese power system in the same scenarios. The DESPlan tool, used for the study, provided technical alternatives for network reinforcement based on Battery Energy Storage System (BESS) solutions. It was always possible to solve congestions by resorting to BESS, although their economic viability for this purpose against other solutions was not investigated in much depth.

Finally, UDE used the nodal prices resulting from their WP2 study to assess the profitability of additional storage units depending on their location and energy/power ratio. For units of 500 kWh/500 kW, the annual benefit on the European system cost was estimated around 10 000€. However, significant difference between locations were highlighted, with margins being typically higher in Germany than in France. Yet even inside Germany, there were substantial differences in profitability and, in contrast to naïve expectations, the highest margins were not observed in the coastal locations with high renewable infeeds. Sensitivity calculations on the storage sizing showed that relative increases in energy content yield higher benefits than increases in the power rating. Units with high power ratings would need to participate in other markets to monetize their short-term flexibility, as their flexibility potential would not be sufficiently rewarded in the energy market.

Those different studies call for further analysis of the best incentives and market designs to support an efficient uptake of the local value of flexibility.

[D1.3] [D1.4] [D2.4]

Figure 41. Box plot of annual operation margins for an exemplary storage configuration depending on their location in UDE nodal study in 2030.



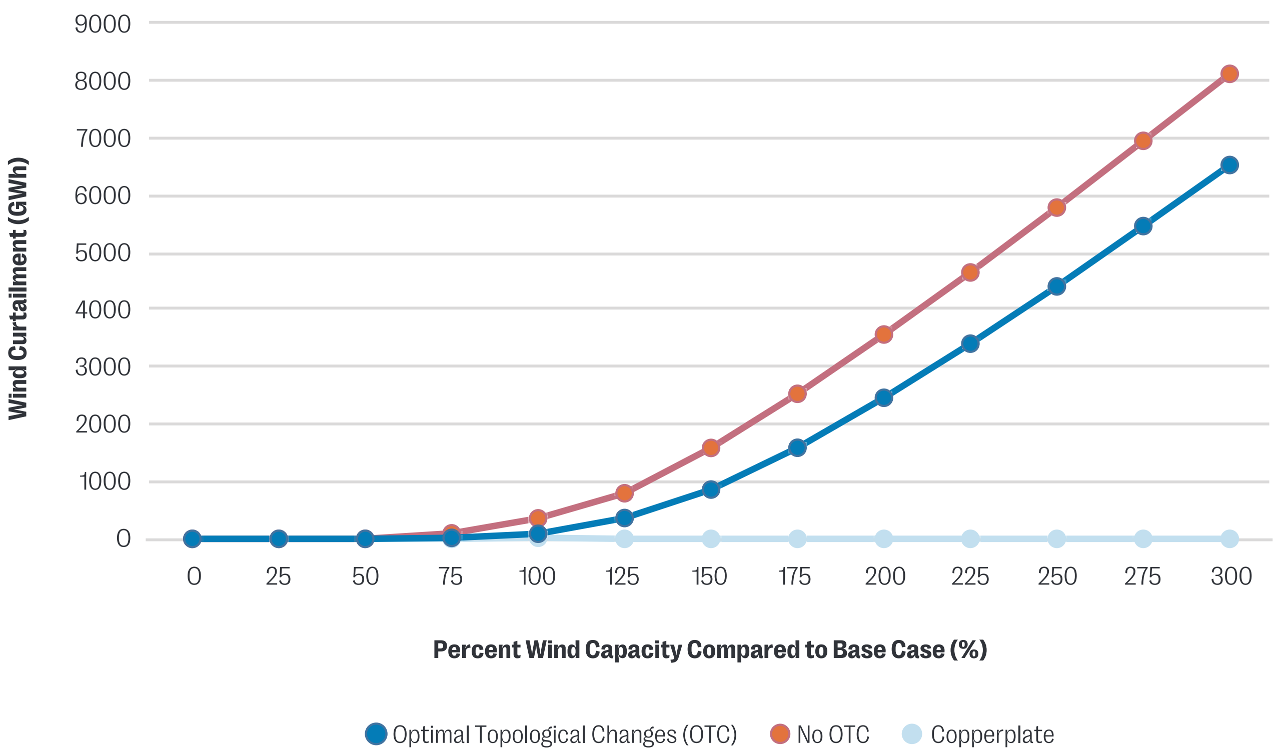
Topological actions have a significant value for congestion management and even more in system with high RES penetration

The topology of the grid is itself a flexibility and opening/closing some switches can frequently release congestion although this possibility is not yet fully exploited in all countries.

To quantify this opportunity, in WP2, RTE modelled a typical 96 nodes network characterised by a high RES penetration. The study points out the value of topological actions but even more, it shows that higher RES penetration leads to an increase of topological actions profitability. In the tested network, an increase in wind production of a factor of 3 leads to a gain in total system cost by a factor of 3.4 from optimal use of topological controls. The development and integration of topological actions within TSOs practices and market designs is thus crucial as variable renewable energies become a larger percent of the dispatch.

ⓘ **[D2.4] [12]**

Figure 42. Sum of Wind Curtailment across All Hours with Thermal Generation.



What did you learn?
What's your next step?

Partners words

Nathalie Grisey
RTE
Project coordinator

Carmen Cardozo
RTE
WP3 leader

“ RTE’s understanding of the possibilities and challenges of providing grid forming capability with inverter-based resources has significantly progressed thanks to the collaboration with the manufacturer Ingeteam and EPFL in OSMOSE. This dialogue is essential to define suitable specifications that lead to a technical feasibility and economic viability of this technology. The results will directly support our discussion with other TSOs and manufacturers regarding future grid codes requirements to ensure power system stability.
On the modelling part, the progress made in OSMOSE for flexibility and market modelling will feed in our current and future tools to analyse the European power system with an improved holistic view.
Finally, the demonstration of a near real-time cross border energy echanges at the Italy -Slovenia border is a great source of inspiration for us to think the future of optimised system operation. ”

Miran Kavrečič
HSE
WP6 Task leader

“ The possibility to actively participate in OSMOSE gave HSE the opportunity to work with flexibility providers, researchers and TSOs in a different way. The project was an icebreaker in terms of Horizon projects for HSE, enabling the company to put itself on the map of organisations which not only participate in the market but also contribute to rethinking markets of the future. HSE contributed to the pilot test of the near-to-real time cross border FlexEnergy market. Flexibility is one of the future challenges and assessing it near-to-real time on a portfolio of large power plants is both a challenge and an opportunity for us. ”

Yves-Marie Bourien
CEA
WP7 leader

“ The WP7 activities within OSMOSE confirm that the coordination between the different stakeholders and components of a flexibility device is of major importance to gain time, efficiency and knowledge. It is true for installing intelligent electronic devices from different vendors, for optimally using the flexibilities into the distribution grid, for getting the best operation of the BESS during the longest possible time and for addressing the different services by a BESS with the right sizing and the optimal energy management. OSMOSE enabled to push some developments, and some more will be required in the near future. ”

Joaquin Álvarez Agudo
GPTech
WP4 task leader

“ In OSMOSE WP4, GPTech has gone through a complete manufacturing process, overcoming most of the scaling up challenges. With the tests on field, connected to a real High Voltage network, GPTech has achieved a high TRL, close to the commercial phase, which is a key milestone on our HV line of innovation.
With OSMOSE and end users, such as REE, GPTech has built a fully functional equipment, capable of integrating multiple energy storage systems and improving electrical grids based on the development of an innovative power electronic architecture focused on network stability. ”

Jens Weibezahn
TUB
WP1 leader

❝ The OSMOSE project gave us the opportunity for a very fruitful collaboration between industry and academia. In WP1 we were able to refine methodologies of existing modelling frameworks as well as develop new frameworks -like AnyMOD.jl- to investigate impacts of a high or full share of renewables on energy systems, the interaction of sector integrated systems, and the need for and behaviour of supply side and demand side flexibility. We identified the interplay of long-term investment optimisations and short-term dynamic simulations as a critical factor for a robust system assessment. The exchanges within the team have shown this in data validation loops and regional/local studies. The developed frameworks, data, and results are now provided to the energy research community and industry in an open manner and will be highly valuable for future studies and projects. ❞

Leonardo Petrocchi
Terna
WP5 leader

❝ OSMOSE Italian demonstrator provided a better understanding on what TSOs should expect from future flexibility resources. Tests results will be helpful to update existing grid codes and guide new pilot projects: a smart grid management, supported by capital-light solutions such as Dynamic Thermal Rating and short-term forecasting, is key to the full exploitation of existing assets. This can be of support to the planning of key infrastructures to be realised in the future. Wind farms showed to be a promising addition for future system stability, while industrial DSR should be considered only for slower balancing services: indeed, flexibility needs can be met not by just one technology, but by a well-balanced mix of all. ❞

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Optimal Mix of flexibilities

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WP2
Market designs and regulations allowing the optimal development of flexibilities with high shares of RES generation

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WP3
Grid forming for the synchronisation of large power systems by multi-service hybrid storage

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WP4
Multiple services provided by the coordinated control of different storage and FACTS devices

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WP5
Multiple services provided by grid devices, large demand-response and RES generation coordinated in a smart management system

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WP6
Near real-time cross-border energy market

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WP7
Scaling up and replication

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Acronym table

aFRR	automatic Frequency Restoration Reserve
AVC	Automatic Voltage Control
BESS	Battery Energy Storage System
BSP	Balance Service Providers
DER	Distributed Energy ressources
DSM	Demand-Side Management
DSO	Distribution System Operator
DTR	Dynamic Thermal Rating
EMS	Energy Management System
ESS	Energy Storage System
FACTS	Flexible Alternating Current Transmission System
FCR	Frequency Containment Reserve
FFR	Fast Frequency Response
HFD	Hybrid Flexibility Device
MC	Master Control
MMC	Modular Multilevel Converter
MPC	Model Predictive Control
NS-TVI	Negative Sequence threshold virtual impedance
OPF	Optimal Power Flow
PCS	Power Converter System
PHIL	Power Hardware in the Loop
PMU	Phasor Measurement Units
RES	Renewable Energy Source
ROCOF	Rate of Change of Frequency
RTPSS	Real-Time Power System Simulation
SCADA	Supervisory Control and Data Acquisition
SCL	System Configuration Language
SI	Synthetic Inertia
SICD	Synthetic Inertia Control Device
SCL	System Configuration Language
SOC	State Of Charge
SOE	State of Energy
STATCOM	Static Compensator
STR	Static Thermal Rating
TRL	Technology Readiness Level
TSO	Transmission System Operator
UC	Ultra-capacitor
VSC	Voltage Source Converter
WP	Work Package

Bibliography

All documents are available on the project website:
www.osmose-h2020.eu

Main public deliverables

[D1.1] European Long-Term Scenarios Description
[D1.3] Optimal mix of flexibilities: Large-Scale Optimisation for Europe
[D1.4] WP1 Summary report

[D2.1] Methodology for error forecasts at an European scale
[D2.3] Models for market mechanisms simulation taking into account space-time downscaling and novel flexibility technologies
[D2.4] Quantitative analysis of selected market designs based on simulations
[D2.5] Recommendations for integrated European market mechanisms and regulatory frameworks fostering the optimal development of flexibilities for the 2050 RES targets and regional specifications

[D3.1] Multi-services control algorithm for converters
[D3.2] Overall specifications of the demonstrations
[D3.3] Analysis of the synchronisation capabilities of BESS power converters
[D3.4] Quantification of multi-service synergy and impact on sizing

[D4.3] Hybrid flexibility device implemented (modular solution)
[D4.4] Master control strategies
[D4.5] Real operation evaluation results

[D5.1] Techno-economic analysis of DSR and RES selected services
[D5.5] Final Report on demo execution results (data analysis)
[D5.6] Final report summarizing main demo results

[D6.1] Mechanism design and specifications
[D6.3] Report on Software demonstration platform development
[D6.5] Demonstration tests
[D6.6] Impact analysis of the performed field tests and exploitation

[D7.1] IEC 61850 ENTSO-E profile refinement and recommendations ended
[D7.2] Execution of all demonstrators (specification, vendor implementation and comparison)
[D7.3] Stakeholders recommendations for IEC 61850 ENTSO-E profile standardization
[D7.4] Tests results of the flexibility scheduler
[D7.5] Methodology report for application-specific design of BESS

Main Publications

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