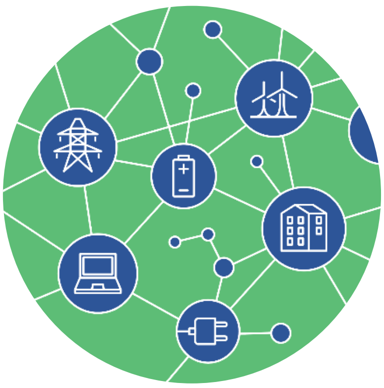
OSMOSE

OPTIMAL SYSTEM-MIX OF FLEXIBILITY SOLUTIONS FOR EUROPEAN ELECTRICITY

WP1 Summary Report

D1.4



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1 Executive summary

The OSMOSE project addressed the question of power system flexibility, understood as its ability to cope with variability and uncertainty in demand, generation and grid, over different timescales. 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 and 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 modeling of flexibility. Work package 1 of the project 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.

WP1 aimed to find a flexibility mix that maximizes the European social welfare, considering all relevant technical constraints and associated costs. Given the variety of technologies and actors, interactions between the entities that require or provide flexibility must be accurately modelled in time and space to assess the real value of flexibility. WP1 focused primarily on addressing methodological issues and developing a general-purpose toolkit suitable for addressing these issues in the context of the European system. Within WP1, Task 1.1 builds scenarios with varying levels of compliance with the CO_2 emission reduction commitments of the Paris Agreement, from today to 2050 and Task 1.2 aimed to optimise the mix of flexibility associated with these scenarios at a “TSO-centric” level to ensure that the power mixes can match the security of supply criteria in force in Europe. The main objective of Task 1.3 was to devise a fully-fledged investment and dispatch model for Europe, endogenizing investments while considering sectoral coupling (with gas and heat), which adds significant value to the analysis of long-term scenarios of the energy sector. Task 1.4 assessed the flexibility options identified by Task 1.2. More specifically, it analysed the optimal sizing and siting of the above-mentioned flexibility options (Sub-Task 1.4.1), assessed the interaction with the grid operations (Sub-Task 1.4.2) and investigated the stability of the system (Sub-Task 1.4.3). Finally, Task 1.5 identified synergies and delivered an integrated assessment of when flexibility options are deployed for multi-service purposes. After investigating the individual value of the different system services from a system perspective, the pros and cons of different combinations of services (“packages”) were assessed using a stylized analytical economic model.

2 Introduction

The OSMOSE project addressed the question of power system flexibility. Beyond a mere buzzword, literature converges to define flexibility as the ability to cope with variability and uncertainty in demand, generation, and grid. System operators have always had to cope with variability and uncertainty. The final goal being an optimal dispatch of the generation, demand, and storage in real-time.

However, the energy transition is changing the flexibility landscape:

- Variable Renewable Energy Sources reshape the variability and uncertainty in the system,
- The switch from synchronous to inverter-based generation challenges its stability,
- The electrification of end uses - heating, mobility, power-to-gas - brings new types of loads in the system,
- Large storage solutions are becoming more competitive,
- Advanced automation and control technologies enable smarter and faster operations.

These changes represent both threats and opportunities for the power system: while flexibility requirements tend to increase, new flexibility sources are appearing, that can help tackle such challenges. Aware of the importance of evaluating the long-term effect of these transformations, the OSMOSE partners have planned in their answer to the H2020 call LCE-04-2017 to complement the demonstrators with prospective studies aimed at:

- Enhancing common understanding of future flexibility requirements and sources by analyzing the evolution until 2050 of prospective mixes targeting compliance with the European commitments of the Paris Agreement,
- Proposing a comprehensive methodology for designing and operating an optimal mix of flexibility.

Flexibility is fundamentally a question of time: what are the actions that can be taken? Which uncertainty and variability are they meant to address? All the time horizons are tightly interrelated which makes a global understanding very challenging.

Furthermore, given the variety of technologies and actors, most interactions between the entities that require or provide flexibility must be accurately modelled in time and space to assess the real value of flexibility. The project focused primarily on addressing methodological issues and developing a general-purpose toolkit suitable for addressing these issues in the context of the European system, rather than providing scenarios.

2.1 OSMOSE approach toward an optimal mix of flexibility

In order to answer the methodological and practical issues, the OSMOSE project opted for an approach which attempts to make “the best of both worlds”:

1. Assessment based on the analysis of the fundamentals of power system economics

At this stage, the project aimed to consider all relevant technical constraints and associated costs (technology, potentials, “natural” loads…), and tries to maximize the social welfare of the area under consideration, establishing an upper bound that then serves as a reference. The main bricks for this assessment are CExMs, PCMs and load flows. At this stage, particular attention should be paid to sensitivity analyses, to ensure sufficient robustness and to distinguish fundamental from circumstantial effects (e.g., nearly “flat” cost function giving rise to many equivalent solutions).

This first step is the focus of WP1 discussed in this report.

2. Introduction of imperfections

Agent-based simulations act as a "fact-checker" for the plausibility of the "behavioural" assumptions made in step 1 (impact of acceptability on VRES potential, on Demand-side management –DSM–…). Economic inefficiencies such as forecast uncertainty, market players and their strategies, and market rules… will result in lower social welfare than that of the "benevolent monopoly" approach. At this stage, the way the added value is shared will also come into play, which is an essential criterion to identify individual stakes and efficiently promote the needed adaptations of rules.

This second step was the focus of the WP2.

2.2 Organisation of WP1 to perform the assessment based on fundamentals

The overall objective of Work Package 1 (WP1) is two-fold: to identify an (cost-)optimal mix of flexibilities for the European power system and to establish a broad understanding of drivers for the deployment of flexibility options by analysing: (A) the balancing of energy demand and supply (power-scheduling level); (B) the use of flexibility options for the provision of system-services (such as frequency and voltage control, etc.), and (C) the impact of the use of flexibility options on operation and planning of transmission and distribution grids. The multi-scale modelling introduced above has been translated into the organization of WP1 into subtasks. The organisation of WP1 can be summarised as follow:

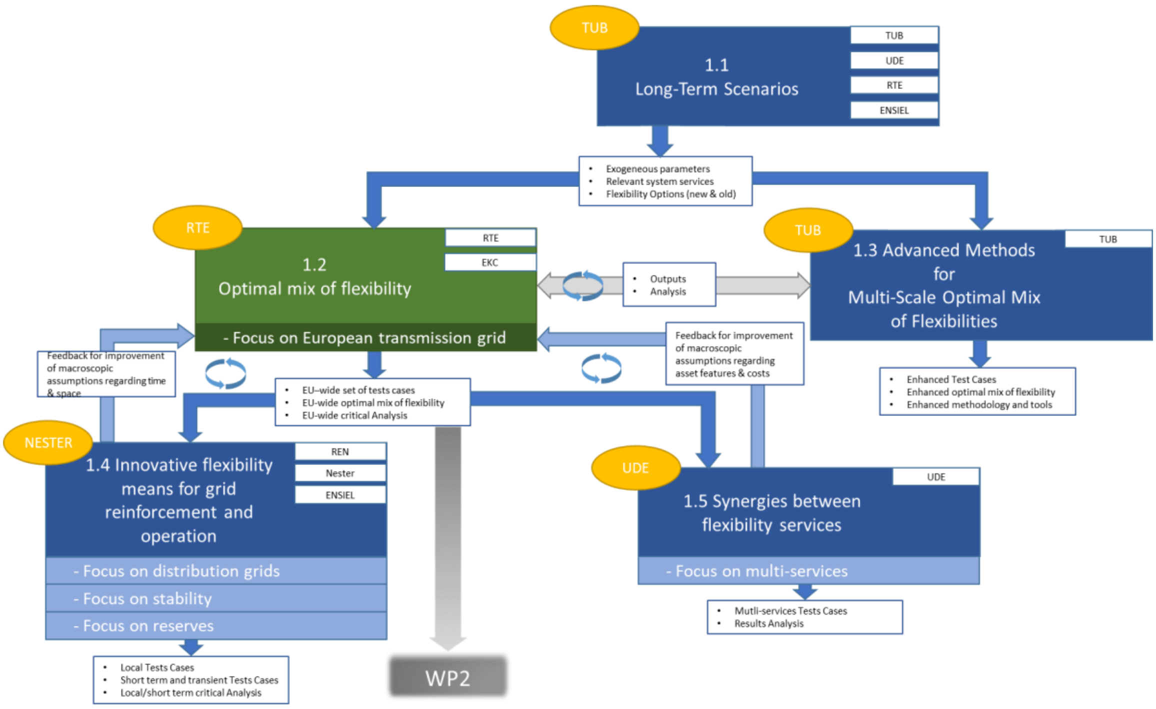

Figure 1: multi-scale structure of the study

- The scenarios used are created by T1.1 ("Long term scenarios"), under the constraint that the energy system respects precise CO2 emission constraints from today to 2050. T.1.1's functional scope is larger than the power system.
- T1.2 ("Optimal mix of flexibility") performed security of supply assessment of the European power mixes produced by T1.1, with clear interfaces with other sectors and vectors, and scope of modelling focused on the transmission grid ("TSO-centric

modelling"). Given the conclusion of this analysis, T.1.2 adapted the power mixes to tried to match the security of supply criteria in force in Europe.

- T1.3 ("Advanced methods for large-scale optimization") dealt with the impact on the other sectors and vectors of the modifications performed by T1.2 to better integrate the flexibility requirements and procurement.
- A geographical and temporal downscaling was performed in T1.4 ("Innovative flexibility means for grid reinforcement and operation"), to address distribution grid issues, focus on reserve procurement, and verify stability. For reasons of resource and data availability, the downscaling was limited to some parts of the European grid.
- T1.5 ("Synergy between flexibility services") tried to model the synergies between flexibility services, with their impacts on the costs and lifetime of flexibility solutions.
- T1.2 supplies the other tasks with generation programs reflecting the behaviour of each technology in a holistic view of the power system, and in turn collects feedback from the other to improve its own modelling, thus materializing a rough decomposition-coordination scheme.

As shown by the circular arrows in Figure 1, the initial idea was then to formally integrate all sub-tasks at a high level of feedback: a description of the additional costs and constraints induced by geographical and temporal downsizing, as well as cross-sectorial modelling and the assessment of multiservice effects. All of this is really necessary to fully understand the economics of flexibility and to size flexibility solutions appropriately.

However, doing so in our modelling would have added a new layer of complexity to an already complex problem. For reasons of efficiency and time limitation, it was decided to investigate the different strategies in parallel. Therefore, the final analysis would have to take into account the individual effects measured in each of these strategies.

3 European long-term scenarios (T1.1)

3.1 Development of long-term scenarios

The OSMOSE project aimed to investigate the need for flexibility and how it can be covered in a future energy system characterized by high shares of variable renewables and low carbon emissions. Flexibility can generally be defined as a power system's ability to cope with variability and uncertainty in demand and generation.

Power generation from variable renewables is only predictable to a certain extent and cannot be dispatched freely: operators can curtail generation, but not increase it. These characteristics create a need for different temporal kinds of flexibility within the energy system. The need for long-term flexibility is largely independent of forecasts and forecast errors (See Figure 2). It is due to fundamental mismatches between demand and renewable supply patterns. Solar power generation during the summer and winter peak load is an example of such a mismatch. Over the medium-term (from hours to weeks), dispatchable generators adjust to forecasts in advance to keep deviations small in the first place. Finally, in the short term, demand/supply deviations stemming from forecast errors have to be balanced out by ancillary services almost immediately to ensure grid stability.

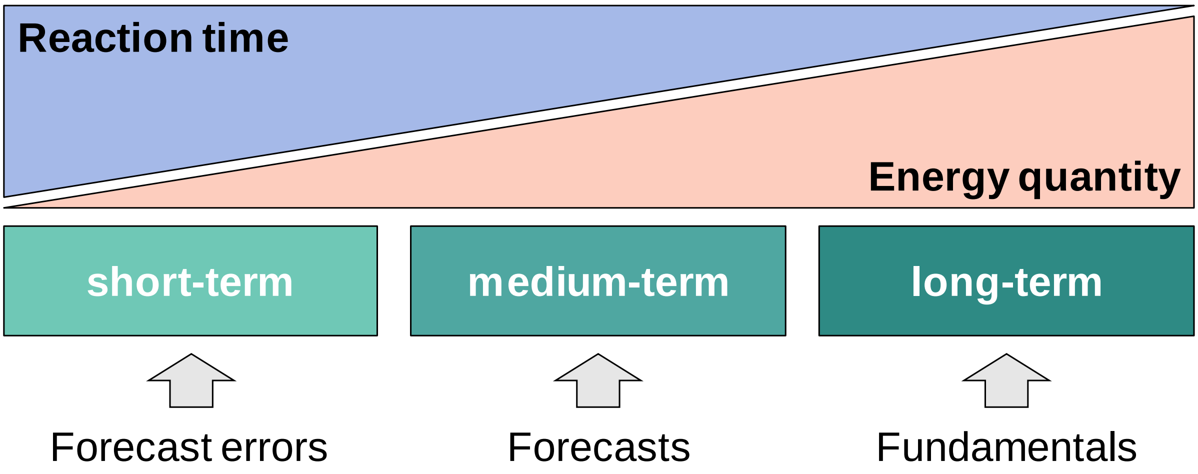

Figure 2: Typology of flexibility requirements

Future needs and sources for flexibility do not solely depend on the power system, but on developments in the heat and mobility sector. Since the sustainable potential of biomass is limited, there are few renewable energy sources available to use directly in these sectors. Consequently, decarbonization in the heat and mobility sector implies increasing reliance on renewable electricity as an energy carrier. This can be achieved by either converting electricity into synthetic fuels or direct use of electricity in electric cars or heat pumps. However, both options result in major sectoral interdependencies and, thus, the integration of the energy system. Scenarios in this task aim to quantify the conceivable range of needs and sources for flexibility arising from these interdependencies. This will enable follow-up studies on investigating the cost-efficient mix of flexibility in future energy systems characterized by variable renewables.

This task maps out the long-term development of the European power system and aims to provide a basis for subsequent studies on the arising need for flexibility in the OSMOSE project. For this purpose, three scenarios named "Current Goals Achieved" (CGA), "Accelerated Transformation" (AT), and "Neglected Climate Action" (NCA) are introduced. Model calculations determine, for each scenario, the development of the overall energy system and, in greater detail, that of power system supply and demand.

The three scenarios differ in terms of what climate protection efforts are successfully undertaken within the EU. In practical terms, varying levels of final energy demand and carbon emissions are set. Reducing carbon emissions implies shifting the supply of electricity, heat, and mobility from fossil fuels (coal, gas, oil, ...) to renewables (wind, solar, biomass, ...). Except for biomass, where the sustainable potential is limited, renewable energies cannot directly substitute fossil fuels in the heat and mobility sectors. Therefore, heat pumps, synthetic fuels, electric vehicles, or any other technology that allow the use of renewable electricity in these sectors will result in growing electricity demand. As a result, the power system, at the centre of this process, is increasingly shaped by the heat and mobility sectors.

To reflect these interdependencies within the calculation process, first each scenario's energy system is modelled. Then, results from the energy system model, such as total electricity demand, serve as inputs to a more detailed power system model. In contrast to existing scenarios, this top-down methodology allows high-resolution analysis of the power system while also capturing its interaction with other sectors of the energy system, especially with respect to final electricity demand.

Results show that both electricity total demand and load profile greatly depend on decarbonisation efforts taken in the heat and mobility sectors. The same applies to the supply side. For example, investment in seasonal storage systems in the power system (e.g., Power-to-Gas) is highly dependent on demand from electric heating appliances.

For more information, see the Deliverable: D1.1: European Long-Term Scenarios Description

3.2 Flexibility cost and operational data outlook

As part of Task 1.1, technologies that can serve as sources of flexibility for the electricity system are described including electrochemical, mechanical, and chemical storage systems as well as flexible thermal power plants. In addition, it is discussed how the demand side and interconnections between regions can provide flexibility as well. Derived from an extensive literature study, current and future cost data has been derived. This report is accompanied by a comprehensive data set of technical parameters and cost data.

For more information, see the Deliverable: D1.2 Flexibility Cost and Operational Data Outlook and the Related Data Set

4 Optimal mix of flexibility (T1.2)

The general goal of Task 1.2 is to analyse the optimal deployment of flexibility options for the European power system based on scenarios and technology data from Task 1.1. The focus is on large-scale considerations: system-wide balancing of energy supply and demand is at the centre of analysis. This is complemented by coherence checks with Tasks 1.3 to 1.5 (so as to gradually and continuously improve the analysis) and sensitivity analyses. Task 1.2 aims to optimise the mix of flexibility associated with these scenarios at a “TSO-centric” level to ensure that the power mixes can match the security of supply criteria in force in Europe. The main findings are summarised below.

Innovative flexibility quantification metrics are needed to address the question of who provides flexibility and how flexibility sources actually interact

The existing literature on flexibility metrics, while rich, does not address the question of who provides flexibility and how flexibility sources actually interact. Two indicators were therefore created to address this gap, covering annual, weekly and daily time horizons:

- Flexibility Solution Modulation Stack (FSMS) expresses how each flexibility solution behaves to match supply to demand over the three time horizons.
- Flexibility Solution Contribution Distribution (FSCD) evaluates the relative contribution of each flexibility solution for the different time horizons.

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. In addition, addressing this weakness greatly improves the reliability of CO_2 emission calculations.

Capacity Expansion Models like GENeSYS-MOD or OSeMOSYS are key in power system planning and energy policy. However, due to size and tractability issues, they rely on time slices, which are known to greatly impair the representation of variability and flexibility needs. One way to solve the limited flexibility representation in capacity expansion models is to couple them with production cost models providing a more accurate hourly dispatch. T1.2 pursued this idea using two soft-linking approaches:

- Heuristic soft linking, where capacity adjustments were performed "heuristically". This approach helped frame and understand the typical problems with the capacity expansion model results.
- Automated bi-directional soft linking, where results from the production cost model are automatically fed back to the capacity expansion model to signal under- and over-investment in order to adjust the investment pathway in the next iteration. Two variants of the feedback scheme were successfully tested: a first one based on reserve margin feedback and a second one based on flexibility contribution metrics (which produced better results).

The assertion that established Capacity Expansion Models significantly underestimate flexibility value was experimentally confirmed in the automated soft-linking process, leading to a 10% increase in TOTEX, and notable changes to the generation mix (balance between base and peak units installed capacity), dispatch and subsequently CO_2 emissions.

Industrial capacity and infrastructure development rate are critical parameters to be considered in capacity expansion planning, especially to meet ambitious CO2 emission targets

Results show that the political and industrial capacity considerations like industries' ability to roll out new infrastructure fast enough significantly impact the model results, especially the achievement of our current CO2 emission reduction targets.

In the studied scenarios, the flexibility requirements at the European level increase slightly until 2030 and then more significantly between 2030 and 2050. These studies demonstrate the value of new flexibility solutions (in particular short- and long-term storage) but confirm that interconnections will still have a major role to play.

Results show a shift from a scheme where annual modulations are linked to consumption and generation maintenance patterns to a new one driven by annual generation patterns of VRES which are irregular throughout the year. Although the situation is country dependent, 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[1], they become a major source of flexibility for all timescales (annual to hourly), potentially replacing hydro. This highlights the need for coordinated management of long-term storage, which has not been done in this simulation.
- In 2050, batteries provide significant flexibility, limited to the daily scale due to their energy rating.
- In 2050, gas turbines, ideally powered by green gas, are an important flexibility provider.

[1] The merit order of decarbonisation solutions depends on the list of options considered to meet the European pledges of the Paris Agreement. This list is the combined result of technological maturity trajectories and political decisions. It has not been discussed in detail in this work, which focuses on methodological aspects.

- 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.

A valuable collaboration effect between electrolysers and short-term flexibility sources (batteries, pump storage plants) may take place, provided that suitable market designs encourage the participation of all flexibility levers in the day-ahead and intraday markets

In 2050 simulations, during some sunny summer peaks, generation is exceeding both the demand and the electrolyser capacities. Then other shorter-term stock-based flexibility providers (such as batteries and pump storage plants) can charge before discharging a couple of hours later, when PV generation decreases, keeping electrolysers running outside sunny (or windy) hours. This optimal collaboration effect could be translated into operational reality by market designs that foster the participation of all flexibility levers in the day-ahead and intraday markets.

Considering sector coupling in capacity expansion models is key but requires modelling adaptations to keep the problem tractable

The limited scope of cross-sectorial modelling was performed, ensuring that the power system will be able to fully run in 2050 on domestic green gas produced via electrolysis. It reveals additional linkages between flexibility requirements and provision capabilities and highlights how crucial it is to take these linkages into account when studying flexibility:

- In 2030, marginal costs (usually deemed as an acceptable proxy for the market-clearing price) exhibit the usual pattern and are mainly driven by generation costs.
- In 2050, though the power system is mostly powered via VRES whose proportional cost is zero, marginal costs are driven by flexible demand. Indeed, electrolysers could significantly increase prices during scarcity periods, drastically limiting the time steps with a market price of zero.

In order to accurately reflect prices, other energy carriers (methane, hydrogen or even heat) should be modelled in detail, taking into account their price sensitivity and their own demand. This would also require modelling inter-annual storage and alternative means of producing or importing each carrier.

Increasing the geographic resolution of the study highlights the sensitivity of overall system flexibility to internal grid constraints and the important role of the grid as a flexibility lever.

Dispatch simulations with a resolution of 99 zones for Europe lead to contrasting results: internal grid constraints increase both spillages, loss-of-load duration and energy not supplied. This analysis points to a reduction of system flexibility due to grid constraints and the significant role of the grid as the flexibility lever (in the 2050 study case, alleviating the internal grid constraints implies an increase in power-to-gas utilisation). Further analysis would be required to assess whether the optimal solution for mitigating this congestion is redispatch, which can represent an additional revenue stream for flexible units or rather more internal grid developments instead.

Reserve management processes should be harmonized, in particular, to explicitly account for the Europe-wide temporal variability of VRES in reserve sizing. Access to interconnections by reserve providers should be fostered through appropriate market design (co-optimisation of reserves and energy in day-ahead and intraday markets).

A proof-of-concept study for integrating forecast error effects and analysing the impact of reserve procurement has been run. Though results are obviously highly dependent on the underlying hypothesis of the scenarios, they give some general hints:

- Reserve requirements are dependent on VRES uncertainty and increase with the share of VRES.
- Grid is a means to share VRES but also flexibility sources on all timescales, including reserves.

Fully efficient use of interconnection for reserve procurement implicitly assumes a co-optimisation of energy and reserve, which will require adaptation of market design to become an operational reality.

The OSMOSE dataset is made publicly available to foster transparency on the assumptions, constructive criticism, and reuse as a benchmark

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 dataset developed by RTE, EKC and TUB is publicly available.

For more information, see the Deliverable: D1.3 Optimal Mix of Flexibility and the full WP 1 Data Set

5 Advanced methods for Large-Scale Optimization (T1.3)

The analyses conducted in Task 1.2 provides a coarse-grained knowledge on economic drivers of flexibility options, based on available tools. The main objective of this task was to devise of a fully-fledged investment and dispatch model for Europe, endogenizing investments while taking into account sectoral coupling (with gas and heat), which adds significant value to the analysis of long-term scenarios of the energy sector.

Based on the findings of the work on long-term scenarios and the role of flexibility in these scenarios in Tasks 1.1 and 1.2 several shortcomings of existing methods were identified. The key insight here was that on the one hand models require high spatio-temporal detail to accurately account for the fluctuations of renewables and their corresponding need for flexibility, but on the other hand, models must cover not just the power sector, but heating, transport, and industry as well to account for all ways this flexibility could be provided in an integrated energy system characterized by high levels of electrification. However, achieving such high detail and great scope exceeds the computational limits of existing modelling methods. To investigate novel methods, we defined a stylized test case for an integrated multi-sector planning model with two example regions based on France and Germany. Since this test case could be solved without novel methods, the objective of subsequent sub-tasks was to develop methods for speeding up the test case without introducing a substantial bias to its results.

To reduce computational complexity and as a result, be able to solve larger models, we developed a new method to formulate planning models used to create long-term energy scenarios. The key idea of this approach is to use different temporal and spatial resolutions for different energy carriers within the same model to reduce computational complexity. For instance, electricity can be modelled at an hourly resolution to account for the fluctuations of renewables and the fact that power grids are highly sensitive to small imbalances of supply and demand, while more inert carriers like gas or hydrogen use a daily resolution. This approach does not only reduce the model size and enables to solving of larger models but can also be argued to be physically more accurate, because it implicitly accounts for the inert flexibility of large-scale infrastructures, like the gas grid. Furthermore, the formulation provides further minor features to account for flexibility, for example, different operational modes of technologies.

Since the mathematical formulation of the developed method is complex, we developed an open-source modelling framework named AnyMOD.jl2 that automizes the creation of specific models using the formulation. To further speed up the test case, the framework is implemented in the highly performative programming language Julia and includes additional features to facilitate solving models with an extensive sectoral scope and a high level of detail. For instance, the matrix of a model's underlying optimization problem is automatically scaled to facilitate the operation of solution algorithms. The modelling framework is openly available including detailed documentation.

We found that the test case could be sped-up by up to 70% by switching to the novel formulation without imposing a major bias on the final results. In addition, the efficient implementation in Julia achieved a speed-up of 60% compared to established modelling frameworks when solving the same model and obtaining the very same results.

For more information, see the publications “A graph-based formulation for modeling macro-energy systems” and “AnyMOD.jl: A Julia package for creating energy system models”, as well as the forthcoming publication “How flexible electrification can integrate fluctuating renewables” (mimeo).

6 Innovative flexibility means for grid reinforcement and operation (T1.4)

Task 1.4 of the OSMOSE project assessed the flexibility options identified by Task 1.2. More specifically, Task 1.4 analysed the optimal sizing and siting of the above-mentioned flexibility options (Sub-Task 1.4.1), assessed the interaction with the grid operations (Sub-Task 1.4.2) and investigated the stability of the system (Sub-Task 1.4.3).

6.1 Optimal Sizing and Siting of Storage Facilities (T1.4.1)

In this task *Optimal Sizing and Siting of Storage Facilities*, which is the responsibility of R&D NESTER, a brief description of the Dispersed Energy Storage tool (DESPlan), the methodology developed as well as simulation results and their correspondent analysis are being presented.

As WP1 focused on the optimal mix of flexibilities, it started by proposing long-term scenarios for 2030 and 2050, which differ in the levels of demand, installed capacities, investment options, and the amount and location of flexibility options. Based on those scenarios, the time series of supply and demand were generated by RTE using its ANTARES model, aiming to assess and validate the referred scenarios.

Using data from T1.1 and T1.2 as input, R&D NESTER redistributed the time series into the model of the Portuguese transmission network, detailed up to the 60kV level (distribution level),

[2] See https://github.com/leonardgoeke/AnyMOD.jl

for 2030 and 2050 time horizons using a methodology developed for this effect. This methodology is explained in detail in the report.

Then, it resorted to the DESPlan tool to perform the simulation of network for the entire dataset (average scenario for both 2030 and 2050) and analysed the results in search for possible congestions that may arise.

The most significant congestion cases were selected for the application of the DESPlan tool to determine the optimal sizing and siting of BESS solutions capable of avoiding the congestions identified. The results of the simulations performed for the selected cases are presented in the deliverable as technical solutions. The congestions observed include:

- Transmission lines;
- Power transformers;
- Combinations of the previous.

As key results from the simulations with the DESPlan toon, it is possible to conclude that:

- For both average scenarios 2030 and 2050, the DESPlan tool identified several potential congestions in several branches in the adapted detailed network models for both time horizons.
- The congestions identified in the 2050 scenario were more frequent and more severe (higher amplitude), than the ones identified in the 2030 scenario.
- Bearing in mind the fact that the simulations were made assuming the network with all its branches available ("N condition"), it's fair to say that even so the approach was benevolent in the sense that more stressful situations (e.g., N-1 contingency criterion), which are typically targeted at transmission network planning, were not addressed in this study.
- The DESPlan tool successfully solved all the selected cases in both scenarios at the minimum cost, as the affected branches continued to be exploited close to their rated capacity.
- Some of the solutions found for the cases presented a very high cost, which may compromise their eventual economic viability from the network planner perspective as an alternative to more traditional network reinforcement options (such as lines or power transformers).
- It is not possible to exclude the effect of the assumptions taken into consideration, especially for scenario 2050, since no major network reinforcements, in both lines and power transformers, were considered from the 2030 model.
- We were surprised to note that in both scenarios (2030 and 2050) Portugal is always importing energy from Spain (and Europe). Even in the 2050 scenario, with PV generation reaching 12GW of production around 12h00, which was more than enough to cover the National load on most summer days for 3 or 4 hours, the country still continues to import energy from Spain in every hour of the year. This behaviour does not look realistic from our perspective.
- Finally, it seems clear that the need for network reinforcement will have to continue in order to prepare the transmission network for the challenges of a near-zero carbon economy, although the plurality of the flexibility options available for investment may be broader.

The DESPlan tool successfully solved all the selected cases in both scenarios at the minimum cost. With the contribution of the BESS, the congested branches were able to continue being exploited close to their rated capacity without overloading.

These studies may help describe potential congestion cases that may arise in the Portuguese transmission network if the network development is carried out as described in this report and conditions established in the OSMOSE scenarios occur.

For more information, see the Internal Deliverable (public): T1.4.1 Optimal Sizing and Siting of Storage Facilities

6.2 Cross-border reserve exchange for improved flexibility and efficiency (T1.4.2)

The task *Cross-border reserve exchange for improved flexibility and efficiency* is within the scope of the work performed by REN. Here, brief descriptions of the main simulation tools used are presented as well as the different analyses and studies performed.

WP1 focus on the Optimal Mix of Flexibilities, starting by proposing long-term scenarios (2030 and 2050), which differ on demand levels, installed capacities, investment options, and on the amount and location of flexibility options. Based on those scenarios, static reserve adequacy analysis was carried-out by RTE using its ANTARES model, aiming to assess and validate the referred scenarios.

Using data from T1.1 and T1.2 as input, REN analyses built scenario credibility for the CSW region (Portugal, Spain and France) as well as medium to long-term adequacy from an operational reserve perspective, using PS-MORA simulation tool. The impacts of considering RES forecast uncertainty are assessed by comparing the reliability indexes resulting from different types of simulations and assumptions.

Simulations studies of the CSW region for different future scenarios allowed to determine the operating reserve requirements and to evaluate cross-border/interconnections benefits arising from a regional coordinated use of flexibility resources. Those studies included:

- *Adequacy Assessment Simulation Studies for CSW Region*, including the evaluation of adequacy of the generation systems and of the available operational reserves using PS-MORA model.
- *Year-by-year Operational Reserve Assessment and the Impact of Interconnection Reserve Capacity During Day-ahead Market*, evaluating the benefits of increasing cross-border/interconnections arising from a regional coordinated use of flexibility resources.
- *Sensitivity Analysis on Flexible Capacity Requirements to be Integrated in the CWS Region*, including the calculation of reliability indexes considering different levels of added flexibility.
- *Benefit Analysis from Increased Interconnection Capacity*, where the impact of considering different levels of interconnection reinforcement within the CSW region is assessed.
- *Sensitivity Analysis on the Increase of RES Generation that PT Region can Accommodate – NECP*, including the impact on thermal-based generation and

interconnection energy flows between PT, ES and FR, as well as CO_2 emission reduction

As main conclusions, it stands out that, for the scenario *Current Goals 2030*, the operational reserve assessment shows inexistence of loss of load expectation (LOLE) and expected energy not supplied (EENS), validating the flexibility options available and previously defined by T1.1 and T1.2. Furthermore, for the scenario *Current Goals 2050* some additional flexibility capacity might be necessary, depending on the reliability criteria assumed, and on the level of RES uncertainty considered. In addition, it was confirmed the positive impact of increasing interconnection capacity in the reliability indexes, namely on the interconnections between Spain and France.

Moreover, hydropower generation management proved to be of key importance in evaluating the impact of hourly power deviations coming from RES units, such as PV and wind, in reliability indicators, which means that the hydro resource management is strategic to ensuring security of supply in the CSW medium and long-term horizons. Portuguese 2030 NECP sensitivity analysis shows that scenario *Current Goals 2030* should consider some RES installed capacity redefinition.

Studies presented in this task illustrate the impacts from the operational reserve perspective that uncertainty from RES generation can have on system reliability indexes and interconnection interchanges.

For more information, see the Internal Deliverable (public): T1.4.2 Cross Border Reserve Exchange for Improved Flexibility and Efficiency

6.3 Stability Aspects (T1.4.3)

This task presents the work on stability aspects, within the scope of the work performed by ENSiEL under T.1.4.3. Here, a brief description of the simulation tool, models, and the studies performed are presented.

WP1 focuses on the Optimal Mix of Flexibilities, starting by proposing long-term scenarios (2030 and 2050), which differ in demand levels, installed capacities, investment options, and the amount of flexibility options. Static reserve adequacy analysis has been carried out by RTE using its ANTARES model, aiming to assess and validate these scenarios.

Using data from T.1.1 and T.1.2 as input, ENSiEL has evaluated the impact of innovative flexibility sources (e.g. renewable energy resources, battery energy storage systems and demand-side response) on power system stability, testing them in a significantly large model of the Italian electrical network, provided by Terna, the Italian Transmission System Operator (TSO). In particular, ENSiEL has assessed some typical perturbations of power systems, e.g., loss of a large generator or slow increase of loads, contingencies of branches, among others, by developing and implementing suitable models of power system components and controls in DIgSILENT PowerFactory.

The given grid has been updated with the new values of capacities and loads given by T 1.1, for years 2030 and 2050. Capacities of the "*Current Goal Achievement"* scenario are implemented for years 2030 and 2050 related to the generators and the following most typical and critical generation/demand conditions have been tested:

- very low load/very low rotating generation in operation;
- high load/low rotating generation in operation;
- maximum export/import of areas;
- operational conditions with weak network (e.g., lines out of service);
- islanding conditions.

The following topics have been then investigated:

- Large-perturbation angle and frequency stability;
- Small-perturbation angle stability;
- Voltage stability.

As main conclusions for *2030*, a couple of cases showed instability conditions that could only be dealt with by flexibility options available. Namely, synthetic inertia provided by wind turbines and suitable PSS control in one case, and frequency containment reserve provided by demand side response in the other. In a few cases, additional flexibility options are needed to ensure suitable post-perturbation conditions. In all other cases, the system snapshots studied were already stable without considering additional flexibility options. Further to the above-mentioned options, also contributions in terms of voltage control from RES-based generation are required to avoid low voltage profiles.

Concerning scenario *2050*, the increased penetration of RES-based generation makes the system conditions closer to instability. However, all operating conditions studied do not show unsolvable stability problems. Furthermore, flexibility options in 2050 seem to be much more necessary to stabilize the system in a higher number of cases. The 2050 scenario is nevertheless characterized by the massive presence of flexibility options provided by RES, as well as by a more significant presence of energy storage, that provides further control variables.

All those considered, the studies carried out make it possible to conclude that such a suitable mix of flexibility options should be adequate to keep the dynamic system security.

For more information, see the Internal Deliverable (public): T1.4.3 Stability Aspects

7 Synergies between flexibility services (T1.5)

The objective of Task 1.5 was to identify synergies and deliver an integrated assessment when flexibility options are deployed for multi-service purposes covering (A) the balancing of energy demand and supply (power-scheduling level); (B) the use of flexibility options for the provision of system-services (such as frequency and voltage control, etc.), and (C) the impact of the use of flexibility options on operation and planning of transmission and distribution grids. After investigating the individual value of the different system services from a system perspective, the pros and cons of different combinations of services ("packages") were assessed using a stylized analytical economic model.

The identification of synergies between flexibility services becomes more important with increasing non-dispatchable energy provision by renewable energy sources. Decarbonization requires high utilization of variable renewable energy sources and hence market design needs to be suitable for all technologies to participate. As a result, the European Commission enforces trade processes for energy and ancillary services to be more standardized, such that competition is enhanced. This enables new business cases for stakeholders, yet it requires them to revise when and where to participate. In the greater perspective – assuming fair competition – this yields the optimal mix of technologies to provide energy and ancillary services.

In this context, the various technologies have different technical restrictions and may provide energy or certain ancillary services. Ancillary services include the provision and release of power for frequency control, grid forming, voltage control, congestion management, fault current contribution, fault ride-through and black start capability. Whereas conventional power plants technically can provide various ancillary services, variable generation can only provide certain services with limited foresight and thus in the short- and medium-term range, exclusively. Furthermore, load-shifting could support frequency control, but not non-frequency ancillary services[3]. Finally, transmission network assets can affect the voltages and currents, hence the power flows in the network.

There is no common consensus on a certain definition of flexibility in the energy system. Various frameworks have been established to assess and compare different dimensions of flexibility, e.g., usage time, response time, uncertainty, and cost. Such measures can be employed to identify efficient technology-to-usage allocations. However, the scope of the state-of-the-art scientific energy models varies. Depending on the study, only certain aspects of the broad definition of flexibility are tackled.

Energy system models that depict optimal future technology-to-usage allocations model endogenous power plant capacities to derive implications for policymakers. These models include energy balancing and partially a simplified representation of reserve capacities for frequency control. Market models pick one calculation year and may also model strategic behaviour of the market participants in some detail. Both markets – for energy and frequency control – are considered to derive bidding strategies of the participants. Research for optimal technology allocation for non-frequency ancillary services, as well as global efficient allocation among energy balancing, frequency and non-frequency ancillary services is still rare. Only technical optimizations, e.g., regarding system security and system resilience, could be identified. Likewise, no studies treat synergies in flexibility provision between normal and abnormal energy system states[4] regarding the corresponding economic aspects.

State-of-the-art energy models cover today's market structures and include energy balancing and reserve markets for frequency control. Approaches are available that reflect the European framework of sequential market clearing. Holistic service allocation models identifying the optimal service allocation are hardly available as of today. Particularly, the inclusion of novel ancillary services such as grid forming in these models has hardly been done.

In a stylized techno-economic model case, we consider the efficient provision of different system services by conventional power plants, renewable energy units and battery storage. In

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[3] non-frequency ancillary service means a service used by a transmission system operator or distribution system operator for steady-state voltage control, fast reactive current injections, inertia for local grid stability, short-circuit current, black start capability and island operation capability (Directive 2019/944 of the European Parliament and of the Council, 2019)

[4] Referring to the services that do not necessarily have to be activated, as long the system does not exhibit contingency events, such as island mode capability, fault current contribution, fault ride-through and black start capability services.

addition to balancing energy supply and demand and frequency control (esp. FCR), the focus is particularly on substitutes to the inertia provided so far by conventional power plants (i.e., inertial response and fast frequency response). Sufficient provision of these alternative services or "inertia substitutes" (sometimes labelled "synthetic inertia"[5]) is required and is going to be seen as a challenge in power systems with low conventional generation.

In addition to conventional power plants, renewable energy sources can provide inertia substitutes: positive reserves from wind energy by a power boost that slows down the rotor speed, negative reserves from wind energy by chopper resistors, or negative reserves from photovoltaic power by new control schemes. Finally, local storage systems such as batteries in electric vehicles or home storage can provide higher self-consumption of photovoltaics, or centralized storage such as hydroelectric plants can provide fast frequency reserves. The participation of renewable energy sources for fast frequency reserves is temporally restrained. The first results of the model show how future generation portfolios may ensure sufficient substitutes for inertia given different shares of updated or modified renewable energy units.

There are many studies evaluating a particular technical device and investigating the extent to which multi-purpose applications can be modelled and implemented. However, such flexibility models are often written for a specific use case or consider only a limited number of services and/or technologies. To the best of our knowledge, obtained from the relevant literature, there are no holistic power system models that cover many different types of flexibility. This is mainly due to the high computational cost of accurately representing nonlinear characteristics in models, as well as the difficulty of combining different time dimensions (dynamic calculation within milliseconds vs. power grid expansion within years). These problems lead to detailed input data for longer time periods and to an excessive computational effort, which implies that research on holistic approaches must follow new routes.

Results from our techno-economic dispatch model incorporating (synthetic) inertia show that the amount of inertia substitutes required from storage units depends on the installed capacity of the wind turbines. In this case, adjusted grid connection rules that require wind turbines to provide inertia substitutes would reduce dependence on battery storage during most hours of the year. Therefore, this storage could be used for other services during most hours.

For more information, see the Internal Deliverable (public): T1.5 Synergies between flexibility services and the forthcoming publication "Provision of inertia substitutes in future electricity systems with low conventional generation" (mimeo).

[5] We avoid the term "synthetic inertia" in line with the findings of WP 3 that emphasize that grid forming encompasses several capabilities (cf. D3.3) of which inertial response is one. But this capability is different from "synthetic inertia", which is usually understood as a software-based emulation of the inertia-like control law. Yet, such emulation is insufficient if an instantaneous response (within 5 ms) to active power imbalances is required.

8 Conclusion

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 and 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 modeling 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. All flexibility needs and sources turned out to be 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.

Notably, future policies should ensure the best use of the flexibility potential of power to gas, batteries, RES, and the 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 addressing increasing variability and uncertainty.

9 Publications

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Göke, Leonard, Jens Weibezahn, and Christian von Hirschhausen. 2021. "Fictional Expectations in Energy Scenarios and Implications for Bottom-up Planning Models". *ArXiv:2112.04821 [Econ]*. http://arxiv.org/abs/2112.04821.

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Heggarty et al. 2020. "Quantifying Power System Flexibility Provision". Applied Energy 279:115852. https://doi.org/10.1016/j.apenergy.2020.115852.

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