MARKET ENABLING INTERFACE TO UNLOCK FLEXIBILITY SOLUTIONS FOR COST-EFFECTIVE MANAGEMENT OF SMARTER DISTRIBUTION GRIDS

Deliverable: D10.4

Scalability and Replicability analysis of the EUniversal solutions

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 864334

H2020 – LC-ES-1-2019

Document
D10.4 Scalability and Replicability analysis of the EUniversal solutions

Dissemination level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Author(s)	Institution	Contact (*e-mail, phone*)
Orlando Valarezo	Comillas	ovalarezo@comillas.edu
Rafael Cossent Arín	Comillas	rafael.cossent@iit.comillas.edu
Matteo Troncia	Comillas	matteo.troncia@iit.comillas.edu
Eliana Ormeño Mejía	Comillas	eormeno@comillas.edu
Néstor Rodríguez	Comillas	nestor.rodriguez@iit.comillas.edu
Ariana Ramos	Vlerick Business School	Ariana.ramos@vlerick.com
Ellen Beckstedde	Vlerick Business School	Ellen.beckstedde@vlerick.com

Key word	Scalability and Replicability analysis of the EUniversal solutions
Due Delivery Date	2023/07/31
Date of Delivery	2023/08/01

Document version	Date	Change
1.0	2023/03/23	Document structure and ToC
2.0	2023/07/10	First draft for internal review
3.0	2023/07/25	Second draft for review
4.0	2023/07/28	Final draft
5.0	2023/07/31	Submitted version

Reviewers		email	Validation date
INESC TEC	Clara Gouveia	clara.s.gouveia@inesctec.pt	2023/07/26
ENGIE Impact	Gerd Küpper	gerd.kupper@engie.com	2023/07/27

Acknowledgements

We would like to thank the three demonstration leaders for providing the necessary input data for the simulations presented in this report. We would also like to thank the respondents of the regulatory questionnaire, internal and external to the EUniversal consortium, for providing valuable information on the countries analyzed in this report.

Without your contributions and support, this report would not have been possible. Please note that any misinterpretation or error remains the sole responsibility of the authors.

Table of Contents

List of figures

List of tables

Acronyms and abbreviations

AP/P	Active Power
API	Application Programming Interface
BUC	Business Use Case
CAPEX	Capital expenditures
CHP	Combined Heat and Power
CIM	Common Information Model
CM	Congestion Management
CMVC	Congestion Management and Voltage Control
CO2	Carbon Dioxide
DE	Germany
DER	Distributed Energy Resource
DG	Distributed Generator
DoA	Description of the Action
DSO	Distribution System Operator
EUR	Euro
FSP	Flexibility Service Provider
HTTP	Hyper Text Transfer Protocol
HV	High Voltage
IAB	International Advisory Board
ICT	Information and Communication Technology
IoT	Internet of Things
KPI	Key Performance Indicator
kV	Kilo-volts
LFM	Local Flexibility Market
LV	Low Voltage
MO	Market Operator (flexibility market)
MV	Medium Voltage
MVA	Megavolt-Ampere
MW	Megawatt
MWh	Megawatt hour
OLTC	On-load tap changer
OPEX	Operating expenditures
PL	Poland

PT	Portugal
PTDF	Power transfer distribution factor
RES	Renewable Energy Source
REST	Representation State Transfer
RNM	Reference Network Model
RP/Q	Reactive Power
SAREF	Smart Applications Reference Ontology
SGAM	Smart Grid Architecture Model
SOC	Second order cone programming
SRA	Scalability and Replicability Analysis
TSO	Transmission System Operator
UMEI	Universal Market Enabling Interface
URI	Uniform Resource Identifier
VC	Voltage Control
VOLL	Value of Lost of Load
WP	Work Package

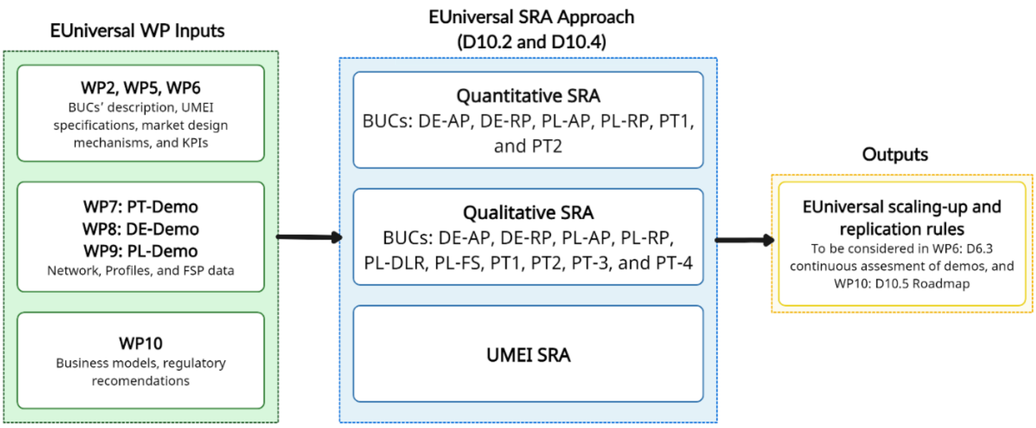
Executive Summary

EUniversal comprises three different demonstrators located in Germany, Poland, and Portugal, in which ten Business Use Cases (BUCs) are being tested on real distribution networks. Complementing the demo results, the Scalability and Replicability Analysis (SRA) presented in this report helps understand the effects of implementing similar solutions under different technical conditions (e.g., network or FSP characteristics) and non-technical boundary conditions (e.g., regulatory conditions or business models). Following the methodology defined in D10.2, the EUniversal SRA is composed of three distinct components (see figure below):

i. A simulation-based quantitative analysis modelling the local flexibility markets for different services and products, and tested for different grids and scenarios (functional SGAM layer).

ii. A qualitative analysis of how regulation, stakeholder views, or business models can foster or hamper upscaling and replication of the BUCs (business SGAM layer).

iii. An analysis of the ease of understanding and reusing the UMEI API specification attending to its design features (information SGAM layer).



EUniversal scalability and replicability approach

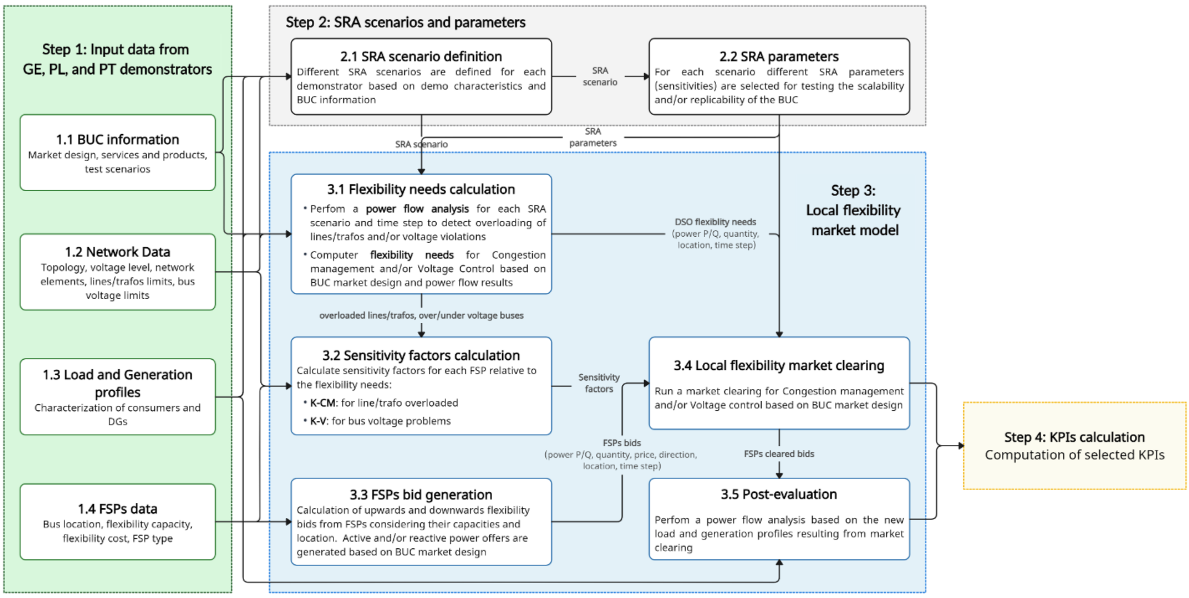
Quantitative SRA: simulating local flexibility markets for different services and products in different distribution networks and scenarios

The quantitative SRA is based on the simulation of local flexibility market operation under different conditions. Different local market configurations combining three service specifications (congestion management, voltage control, or joint congestion management & voltage control) and three product availabilities (active power only, reactive power only, joint procurement of active and reactive power) were tested for four grids in the three demo countries, as shown in the table below.

Quantitative SRA approach: networks and BUCs considered

Demonstrator	BUC ID	Network ID	BUC LFM models	Additional LFM models	Modelling approach
Germany	DE-AP DE-RP	DE-NET1-LV DE-NET2-LV	**CMVC-P** **CMVC-Q**	CMVC-PQ CM-PQ/P/Q	Linearized local flexibility market model considering active and/or reactive power sensitivity factors for network representation
Poland	PL-AP PL-RP	PL-NET1-MV			
Portugal	PT1 PT2	PT-NET1-MV-LV	**CM-P** **VC-PQ**	CMVC-PQ CM-PQ/Q VC-P/Q	

In order to carry out the analyses, a linearized LFM modelling based on sensitivity factors was implemented. The overall methodological framework and process of analysis is shown in the figure below. Firstly, the distribution network models and the scenarios to evaluate are defined. Next, flexibility needs and relevant sensitivity factors are computed. Then, the FSP bids are simulated depending on the capabilities of each type of FSP. Subsequently, the local flexibility markets is cleared minimizing the cost of solving the previously calculated flexibility needs. After this, a post-evaluation is carried out to ensure that the market solution does not violate the grid operational limits. Lastly, the relevant KPIs are calculated including: number/share of avoided restrictions, cost of flexibility procurement, avoided CO2 emissions, increased RES and DER hosting capacity, and increase of energy storage solutions penetration.



Quantitative SRA modeling and simulation process

Comparing the results obtained for each network under the different local market specifications and the results obtained for the different distribution grids, the following are the main general findings that have been identified:

- Markets where both active and reactive power flexibilities are jointly procured generally result in lower costs and are able to solve the same or more constraints. Moreover, active power only markets are generally more effective than reactive power only markets. In fact, results suggest that relying solely on reactive power may not be sufficient to effectively mitigate criticalities within the network. This conclusion stands regardless of the type of service procured.
- The previous conclusion can be explained by the fact that only MV and LV grids with relatively high R/X ratios are evaluated. Moreover, reactive power costs have been assumed to be significantly lower than active power costs, especially for inverter-based FSPs and synchronous generation (CHP, if available). Lastly, the co-optimization of active and reactive power allows for unlocking the voltage regulation potential offered by the capability curve of the resources, allowing for an operating point that optimizes flexibility provision.
- Multi-service markets, i.e., single market for congestion and voltage management, are generally more effective and efficient than single-service markets. However, they may be considered too complex for implementation. It is generally observed that each market model has a direct impact on the related criticality, i.e., CM markets reduce the congested lines and VC markets improve bus voltages, but it cannot be ensured that solving one type of constraint solves the other. In fact, in some cases, solving one type of constraint actually caused additional problems concerning the other type as shown in the post-evaluation. This happened, for instance, when significant (low-

cost) reactive power flexibilities were activated to solve congestions causing voltage limit violations not seen within the market itself (no prior grid prequalification or "traffic-light" limitations were placed on the bids).

- Concerning the previous point, voltage control only markets were closer to the multi-service market models in terms of their effectiveness in avoiding restrictions as compared to pure congestion management markets. This implies that the same FSPs that solve bus voltage violations (with a stronger locational nature) can reduce the loading of upstream congested elements (even if located in different voltage levels), whereas flexibility bids cleared in the congestion management market models do not contribute to solving bus voltage issues. This happens when voltage issues share the same root cause as congestions, i.e., when flexibility solutions are not conflicting, and the two needs can be solved simultaneously. This happened in, for instance, the Portuguese grid, but not in the Polish one where congestions (coupled with overvoltages) and undervoltages took place in different parts of the grid at different times of the day (see figure below).
- On the other hand, in the Portuguese case where congestions happen in the MV grid and undervoltage issues on the LV, the standalone congestion management market is not able to solve any voltage problems because the least expensive flexibility source to solve MV congestions is connected to the MV grid, with no or negligible impact on the LV voltages. Therefore, in the scenarios studied for the Portuguese demonstrator, the voltage control actions are also beneficial for congestion management, acting as an implicit network congestion management measure.
- Voltage limits have a very strong impact on the number of grid criticalities and flexibility needs. Results show that increasing the maximum steady-state voltage variation limits from ±5% to ±7% results in a significant increase in the hosting capacity without any additional action. It remains to be seen whether flexibility may help DSOs relax some (conservative) operational limits.
- Likewise, results suggest that liquidity in local flexibility, which can be a major limitation to their effectiveness, is complex to quantify. This is because flexibility needs must be met in terms of quantity, location, direction (e.g., upward flexibility cannot be easily provided by RES generation) and time (e.g., some FSPs are not available to solve constraints caused by electric heating at night).

Qualitative SRA: open issues in regulation and business models that may drive or hamper upscaling and replication

The qualitative SRA is divided into three parts:

- Firstly, it presents an overview of open questions in congestion management in European Distribution grids, addressing relevant open issues like 'do we plan to have more congestion in distribution grids, or do we need better planning to avoid congestion? Does incentive regulation need to be enhanced to make sure DSOs consider flexibility as an alternative to investments? In what situation will we use which approach to source flexibility and how do we ensure coordination between TSOs and DSOs?

  Results show that DSOs in some European countries increasingly face congestions despite conservative connection rules. However, amendments needed in current distribution planning practices and DSO revenue regulation are not completely clear, the tradeoffs between different regulatory schemes and how they consider OPEX, TOTEX and CAPEX remuneration is discussed Third-party market platforms are tapping into this opportunity, presenting diverse products, time-frames, and interactions with existing markets and system operators. Besides congestion management, the procurement of flexibility for voltage control is also expected to become important for distribution grids.
- Secondly, the qualitative SRA presents an analysis of the replicability potential versus the local nature of the Business Model for flexibility as developed in EUniversal. It is concluded that important components of the business model are replicable thanks to the availability of a

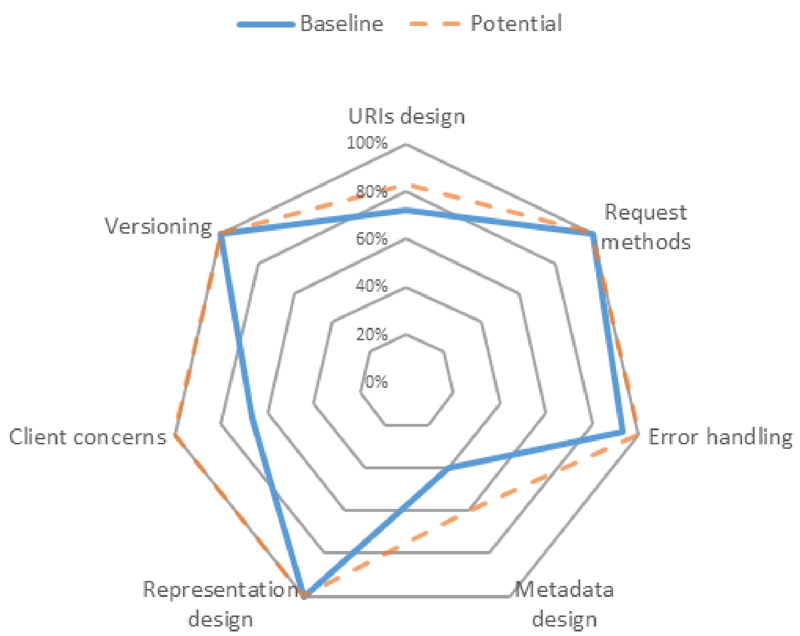
common standard with the UMEI, along with the definition of a value proposition and conceptual definition of revenue and cost concepts.

- Lastly, the qualitative SRA concludes with three main recommendations to enable use of flexibility for congestion management: 1/ the use of heatmaps to indicate areas where congestion and voltage issues might occur and the developments of guidelines and best practices on the trade-offs between flexibility and grid investment is recommended, 2/ keep an open mind regarding the available tools to contract flexibility, the effect of combining different approaches is still not certain, 3/ design open, tangible and up-to-date legal frameworks for regulatory sandboxes to foster innovation in the use of flexibility in distribution grids.

Analysis of the replicability potential of the UMEI API specification

The EUniversal UMEI is a publicly available API that supports the interactions between the different actors and the new flexibility markets. By design, the UMEI API is conceived to be agnostic, adaptable, and modular, and to provide interoperability between DSOs, market parties, and platforms. This means that all the stakeholders should be able to implement it, regardless of the data models and standards they use in their systems. Nonetheless, the implementation of an API may be facilitated or hampered by its design rules. To evaluate the ease of replicability of the UMEI API, a list of best practices has been identified. Compliance with these best practices was then evaluated through a questionnaire filled-in by the UMEI original developers.

The figure below summarizes the main results obtained regarding the UMEI compliance with the best practices for REST API design. The score for each category, represented by a percentage, has been calculated by dividing the number of “Yes” (i.e., practices followed) by the total number of practices that could be applicable to UMEI. It must be highlighted that the UMEI API allows certain degree of freedom for implementation, so some specific practices may be followed by some users and not others. For this reason, this figure shows two cases. The blue line represents the baseline case or worst-case scenario, that is, an implementation of the UMEI where none of the implementation-dependent practices are followed, while the orange dashed line represents the potential case, which considers that all the best practices that may be followed during implementation are indeed applied.



Compliance of the UMEI API with the best practices for the design of REST APIs that have an impact on its scalability and replicability

Overall, the UMEI presents a good level of compliance of best practices of REST API design. UMEI follows all the rules for using HTTP request methods, versioning, and representation design. In certain implementations, the UMEI can also apply all the rules related to client concerns and error handling. The category where the UMEI rates lower quality is metadata design, followed by the category of client concerns when considering the baseline case. Nevertheless, the best practices included in these two categories are the ones commonly considered by expert developers as the least relevant rules for API design. Hence, thanks to its understandability and reusability, developers should not find many inconveniences when implementing UMEI according to its specification.

Despite this good performance of the UMEI regarding REST API design, there is still room for improvement concerning the seamless integration of additional actors and widening the scope in terms of market processes covered. Regarding the former, the UMEI may present some limitations as it relies on a given data model and format for the flexibility services that may not be universal. Regarding the latter, it is relevant to point out that the UMEI, as it stands now, focuses exclusively on the trading process, leaving out other relevant processes that could be integrated, such as the registration of flexibility resources. In order to address these limitations and facilitate replicability, future developments of the UMEI could provide compatibility with other ontologies in the smart grid ecosystem (e.g., SAREF). This could facilitate the registration and prequalification of smart devices and their overall integration in the market processes where UMEI is implemented.

1. Introduction

1.1 Aims and scope of the report

The EUniversal project, funded by the European Union, aims to develop a universal approach on the use of flexibility by Distribution System Operators (DSO) and their interaction with the new flexibility markets, enabled through the development of the concept of the Universal Market Enabling Interface (UMEI), which is a unique approach to foster interoperability across Europe. The UMEI represents an innovative, agnostic, adaptable, modular and evolutionary approach that will be the basis for the development of new innovative services, market solutions and, above all, implementing the real mechanisms for active customers' (e.g., consumer, prosumer, and energy communities) participation in the energy transition.

In order to fulfill this goal, the EUniversal project comprises three different demonstrators located in Germany, Poland, and Portugal, in which ten Business Use Cases (BUCs) are being tested on real distribution networks at different locations. Most of these BUCs are focused on implementing local flexibility markets for the procurement of flexibility by DSO in the short- and long-term timelines. In addition, they are concentrated on the delivery of congestion management or voltage control services through active and/or reactive power.

The results obtained from the demonstrators will provide helpful information on the impact of the BUC solutions. However, these results will be subject to the boundary conditions of each location, such as technical, regulatory, environmental, and social contexts. Therefore, it is necessary to perform a Scalability and Replicability Analysis (SRA) to understand the effects of implementing similar solutions under different technical boundary conditions (network characteristics and technical constraints) and non-technical boundary conditions (regulatory issues, associated business models' constraints, and the perspectives of key stakeholders), that may affect the outcomes expected from the EUniversal project. Therefore, this deliverable (D10.4) presents the outcomes of the SRA of the EUniversal BUCs and the UMEI, more importantly, the main conclusions and recommendations obtained from this analysis.

1.2 EUniversal SRA approach

Figure 1.1 provides an overview of the EUniversal SRA approach, which is divided into three main parts i) a quantitative SRA of the EUniversal BUCs, ii) a qualitative SRA of the EUniversal BUCs, and iii) an analysis of the scalability and replicability potential of the UMEI. It is worth noting that the inputs utilized for conducting this SRA mainly originate from various tasks within the EUniversal project. These inputs include the BUC's description and UMEI specifications of WP2, the market design mechanisms studies and KPI (key performance indicator) definitions of WP6, the anonymized grid data, generation and load profiles, and FSP (flexibility service provider) information from the three demonstrators outlined in WP7 (Portugal), WP8 (Germany), and WP9 (Poland), and the business models and regulatory studies performed on other tasks of WP10.

Furthermore, the results of EUniversal SRA (scaling-up and replication rules) will support the deliverable D10.5, "Roadmap – strategy for the further deployment of the EUniversal solutions". The roadmap will identify a coherent set of key results and main project messages to be exploited. Additionally, two project-level KPIs (Increased RES and DER hosting capacity and Increased energy storage penetration) are calculated in this deliverable based on the results of the quantitative SRA. These KPIs will serve as inputs for deliverable D6.3, which is focused on the continuous assessment of the EUniversal demonstrators.

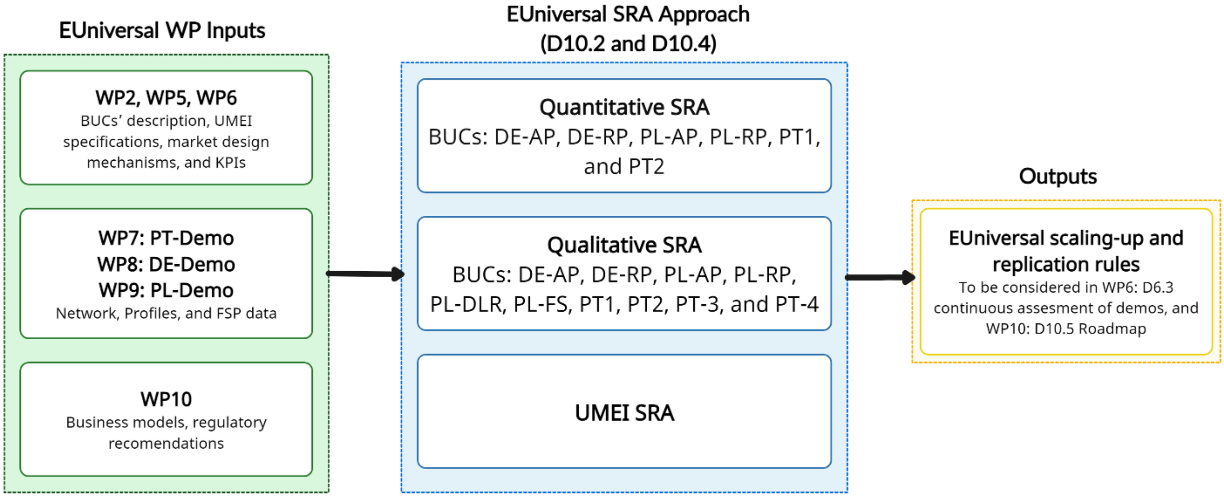


Figure 1.1: EUniversal scalability and replicability approach

With regards to the SRA methodology, it was previously defined and described in deliverable D10.2 [1], considering the following key points:

- The EUniversal SRA scope is characterized by the functional and business layers of the SGAM framework. Concerning the functional layer, the dimensions addressed include the use case's scalability and replicability. For the business layer, the regulatory analysis and the stakeholder perspectives dimensions are considered.
- A quantitative SRA methodology was selected for the functional-oriented dimensions. This methodology is based on a simulation analysis of the BUCs under different scenarios to assess the effect of the parameters that comprise the technical boundary conditions. The choice of simulation approach, selection of relevant KPIs, identification of required scenarios and sensitivities, and data requirements were defined in D10.2, and they are further described in Section 2 of this report.
- On the other hand, a qualitative SRA was selected for the business-oriented dimensions. This methodology focuses on analyzing the non-technical boundary conditions that can affect the potential for replication and upscaling of the BUCs, and it is divided into three parts. First, it presents an overview of open questions in congestion management in European Distribution grids. Second, the qualitative SRA presents an analysis of the replicability potential versus the local nature of the Business Model for flexibility as it has been developed in the project. Finally, the qualitative SRA concludes with recommendations to enable the use of flexibility for congestion management. The qualitative SRA is examined in Section 3 of this deliverable.
- Furthermore, given that the SRA scope and methodology must be tailored to the objectives of each BUC and that the project focuses on local flexibility markets, D10.2 evaluated the EUniversal BUCs identifying which BUCs are part of the quantitative or qualitative SRA. This evaluation was based on the market design characteristics in each BUC and the prioritization (obligatory/mandatory, optional, and business need) of the BUCs indicated in D2.2 [2]. Summarizing the evaluation presented in D10.2, the EUniversal SRA considers all BUCs defined in the project. The quantitative SRA is focused on six BUCs, DE-AP, DE-RP, PL-AP, PL-RP, PT1, and PT2, as illustrated in Table 1.1, and the qualitative SRA examines the ten EUniversal BUCs described in Table 1.1 and Table 1.2.
- In addition, as the development of the UMEI stands as a key objective of the EUniversal project, Section 4 of this deliverable introduces a methodology for assessing the scalability and replicability potential of the UMEI, along with the corresponding outcomes.

Table 1.1 EUniversal BUCs to perform Quantitative and Qualitative SRA, source EUniversal D10.2 [1]

Demo	BUC ID	BUC Name	Mechanism	Timeline	Service	Product
Germany	**DE-AP**	Congestion management & Voltage Control with market-based active power flexibility.	Local flexibility markets	Day-ahead, Intraday	Congestion management and Voltage control	AP
	DE-RP	Congestion management & Voltage Control with market-based reactive power flexibility.				RP
Poland	**PL-AP**	Congestion management & Voltage Control with market-based active power flexibility.				AP
	PL-RP	Congestion management & Voltage Control with market-based reactive power flexibility.				RP
Portugal	**PT1**	Congestion management in MV grids for the day-ahead market (or between 1 to 3 days in advance).		Day(s)-ahead	Congestion management	AP
	PT2	Integrated Voltage Control in MV and LV grids for the day-ahead market (AP+RP).			Voltage control	AP/RP

Table 1.2 EUniversal BUCs to perform only Qualitative SRA, source EUniversal D10.2 [1]

Demo	BUC ID	BUC Name	Mechanism	Timeline	Service	Product
Portugal	**PT3**	Contracting flexibility services for avoiding voltage and/or congestion issues during planned maintenance action in MV grids.	Local flexibility markets	Day(s)-ahead Weeks-ahead	Congestion management, Voltage control	AP/RP
	PT4	Voltage control and congestion management for medium and long-term grid planning through market mechanisms		Days-ahead Years-ahead	Predictive congestion management, Predictive voltage control	AP
Poland	**PL-DLR**	Congestion management using permissible line capacity based on Dynamic Line Rating (DLR) system.		Day-ahead	Congestion management	RES generation above the connection agreement limit
	PL-FS	Voltage control with the use of flexstation solutions.	Bilateral contracts		Voltage control	Flexstation solutions

1.3 Structure of the document

The remainder of this deliverable is organized as follows. Following this introductory chapter where the EUniversal SRA approach was presented, subsequent chapters provide comprehensive information regarding the implementation of the three EUniversal SRA components, along with their respective outcomes. Section 2 is focused on the Quantitative SRA of the selected BUCs, Section 3 addressees the Qualitative SRA of all EUniversal BUCs, and Section 4 concentrates on the UMEI SRA. Last, chapter 5 provides general conclusions and final remarks about the EUniversal SRA results.

2. Quantitative SRA

This section aims to present and analyze the results of the EUniversal Quantitative SRA. Table 2.1 specifies how the approach of this SRA has been defined. Firstly, it is necessary to state that the minimum unit of analysis considered is the BUCs selected in Table 1.1 of the previous section (BUC ID). Moreover, it was necessary to define the geographical scope of the SRA (Network ID). To select demo sites, we considered the BUCs of interest and additional aspects described below.

For instance, in the German demonstrator, the BUCs DE-AP and DE-RP are being tested in three demo sites near the towns of Falkenger, Brandis, and Frankenberg [3]. In order to limit the number of analyses to carry out, only two out of three demo networks were considered for the SRA. The first two of these sites present LV residential networks with very similar characteristics in terms of the number of connected meters and flexibility service providers (FSPs); therefore, only the first one (referred to as DE-NET1-LV) is considered in this SRA. The third site (herewith referred to as DE-NET2-LV) is a LV network consisting of a mixture of large apartment buildings and single-family households, which has a higher number of FSPs compared to the other two demos sites. Regarding the Polish demonstrator, the BUCs PL-AP and PL-RP are being tested in a MV network (PL-NET1-MV) [4], also considered for the SRA. Furthermore, although the PT1 and PT2 BUCs are being tested in different locations [5], the network (PT-NET1-MV-LV) is considered in the SRA because both MV and LV networks could be analyzed, and this network has different types of FSPs such as household loads, PV generation and storage.

As mentioned before, all BUCs of interest are focused on implementing local flexibility markets (LFMs) for congestion management and/or voltage control using active and/or reactive power in a short-term timeline. Therefore, a linearized LFM was implemented according to the market design characteristics of these BUCs. As indicated in Table 2.1, the quantitative SRA will test the scalability and replicability performance of the LFM models of the selected BUCs (BUC LFM models), and other additional LFM models are considered for further analysis. The following subsections provide details of the quantitative SRA methodology and present the outcomes of this SRA for each demonstrator.

Table 2.1 Quantitative SRA approach

Demonstrator	BUC ID	Network ID	BUC LFM models	Additional LFM models	Modelling approach
Germany	DE-AP DE-RP	DE-NET1-LV DE-NET2-LV	**CMVC-P** **CMVC-Q**	CMVC-PQ CM-PQ/P/Q[1]	Linearized local flexibility market model considering active and/or reactive power sensitivity factors for network representation
Poland	PL-AP PL-RP	PL-NET1-MV			
Portugal	PT1 PT2	PT-NET1-MV-LV	**CM-P** **VC-PQ**[2]	CMVC-PQ CM-PQ/Q VC-P/Q	

[1] Reactive power-only markets, albeit uncommon, are considered in the BUC definition presented in D2.2, although it is true that Q-only BUCs address jointly congestions and voltages; no use case addresses CM only with Q. Nonetheless, this specification was added to the analysis as additional results for completeness.

[2]In practice, in the Portuguese demo, reactive power control is provided by DSO assets, being flexibility services only based on active power. This was a simplification considered for implementation purposes. However, both active and reactive power services were considered in the SRA simulations, since reactive power control could also be relevant, particularly for the MV grid.

2.1 Quantitative SRA methodology

This subsection aims to summarize the main steps of the EUniversal quantitative SRA methodology presented in D10.2 [1]. To perform the EUniversal quantitative SRA, the modelling and simulation process illustrated in Figure 2.1 is followed according to the below steps:

- **Collection of input data from demonstrators (Step 1):** The quantitative SRA requires running extensive simulations using power flow studies and optimization problems. Different input data was gathered for each demo site to perform these simulations, including BUC's descriptions, network data, load and generation profiles, and FSPs' characteristics. This information is further detailed in the SRA analysis of each demonstrator, see Sections 2.2, 2.3 and 2.4.

- **Definition of SRA scenarios and parameters (Step 2):** Different scenarios are defined for each demonstrator based on demo characteristics and BUC information. In EUniversal, the BUCs are based on the assumption that grid congestions (overloading of lines/transformers or voltage violations) can be forecasted in terms of location and quantity. Hence, to select an appropriate SRA scenario, a power flow analysis is conducted using the original load and generation profiles as a baseline (Scenario 0). If this initial scenario results in grid congestions, it is chosen for the SRA. However, if no congestions occur, the original profiles are modified iteratively until grid congestions manifest (Scenario 1, 2, etc.), and the modified scenario is selected for the SRA. This process ensures that the selected scenario adequately represents the occurrence of grid congestions in the demo site for further analysis in the SRA.

  For each scenario, different SRA parameters (sensitivities) are selected for testing the scalability and replicability potential of the BUCs. SRA scenarios and parameters are further described in the SRA analysis of each demonstrator of Sections 2.2, 2.3, and 2.4.

- **Local flexibility market model (Step 3):** A local flexibility market model for congestion management and/or voltage control using active and/or reactive power is implemented under the following stages[3]:

  - **Flexibility needs calculation (Step 3.1):** To do this, the distribution network data and load and generation profiles are utilized to run a time series power flow using the pandapower tool [6]. Then, the DSO's flexibility needs are calculated in terms of congestion management (lines and transformers overloading in MVA) and/or voltage control (bus voltage violations p.u). These DSO needs[4] are inputs for the local flexibility market-clearing described later.

  - **Sensitivity factors calculation (Step 3.2):** A local flexibility market-clearing could be solved with or without considering the network data. There are different solutions to incorporate network data and flow constraints in market models for distribution systems, such as second order cone programming (SOC) formulations [7], quadratically constrained programming [8], or linearization proposals of the power flow constraints [9]. However, these solutions can still pose challenges for implementation in practice, particularly with networks of thousands of nodes, as in the case of the EUniversal demonstrators. Therefore, the sensitivity factors are considered as a solution for network representation in the LFM market-clearing of this SRA. In

3 LFM were assumed independent from the wholesale market sequence (no bid forwarding, and power balance in case of activation is exogenous). This is in line with the demos. Moreover, since constraints are in the MV and LV grid, the influence at wholesale level would be minor in most cases (individually).

4 In the simulations, flexibility needs are computed per network component. However, this can be simplified, as done in the demos, by translating these needs per component into flexibility needs per area, i.e. the total flexibility needed to solve grid constraints from a group of relevant nodes which are able to effectively contribute to solve the problem.

fact, the tools developed in WP for the need assessment and market offers are actually based on sensitivity factors, see D4.1 [10] and reference [11].

Within the EUniversal SRA approach, the DSO calculates sensitivity factors for each FSP relative to each flexibility need, and their resulting values depend on the FSP's location and the FSP impact on solving grid constraints. To compute sensitivity factors, the following procedures are considered for congestion management and voltage control:

Congestion management: Congestions are generally caused by the limited power capacity of some branches or transformers. Therefore, it is necessary to analyze the sensitivity of the power flow of the critical branches/transformers to the FSPs active and reactive power injections. These sensitivities are based on the below formulation, where the change in the apparent flow of line ij associated with active and reactive power injections at node k and equivalent withdrawal at node m is:

$$\Delta S_{ij} = H_{ij,km}^{P} \Delta P_{km} + H_{ij,km}^{Q} \Delta Q_{km}$$

Therefore, $H_{ij,km}^{P}$ and $H_{ij,km}^{Q}$ represent the congestion management sensitivity factors with regards to the active and reactive power injections, respectively.

Voltage Control: A matrix M can be derived whose elements represent the sensitivity between the nodal voltage magnitude changes and the nodal active/reactive power injections. Therefore, we can derive the sensitivity factors (M matrix) as follow:

- Using matrix notation, the power flow equations can be expressed as [12]:

$$\begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} = \begin{bmatrix} \frac{\partial\theta}{\partial P} & \frac{\partial\theta}{\partial Q} \\ \frac{\partial V}{\partial P} & \frac{\partial V}{\partial Q} \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = J^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}$$

- Where ΔP and ΔQ represent the nodal active and reactive power injection vectors, respectively, furthermore, $\Delta\theta$ represents the vector formed by the variation of node phases, ΔV represents the vector formed by the variation rate of node voltage magnitudes, and J is the Jacobian matrix. Since our focus is the bottom part of the matrix J^{-1}, the M matrix can be computed as:

$$\Delta \mathrm{V} = \begin{bmatrix} \frac{\partial V}{\partial P} & \frac{\partial V}{\partial Q} \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = M \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}$$

$$M = \begin{bmatrix} \frac{\partial V}{\partial P} & \frac{\partial V}{\partial Q} \end{bmatrix}$$

FSPs bid generation (Step 3.3): In this step, active and/or reactive power offers from FSPs are generated based on their maximum and minimum capacities and according to each FSP technology type. Here, the direction indicates: i) Volumes of increase and reduction of generation (upward and downward flexibility, respectively), and ii) Volumes of reduction and increase of demand (i.e., upward and downward flexibility) at a distribution node. The cost for the flexibility activation is also included in the bid because the FSPs are considered as active traders deciding on their flexibility price. Therefore, these bids are calculated based on costs, which is not necessarily how FSPs may offer in actual markets, particularly under pay-as-bid pricing rules. For the sake of simplicity, market clearing is based on simple bids for each time step (hourly in this case). However, the bid generation does incorporate some of the specific constraints of each FSP type (synchronous generator, inverter-based generator, storage, demand) when computing the bids.

- **Local flexibility market-clearing (Step 3.4):** In the local flexibility market-clearing, the most efficient flexibility bids from FSPs are selected to mitigate the identified DSO flexibility needs at minimum cost. The LFM formulation described in Annex II of this report is considered for this step, where this model is adapted to the definition of each BUC of interest, i.e., services and product characteristics, timeline, etc. The inputs of the market-clearing are:

  - DSO flexibility needs for congestion management and/or voltage control calculated according to step 3.1.
  - Sensitivity factors computed in step 3.2, these sensitivity factors will affect merit order on the market since the combination of the bid price, quantity, and location in the form of sensitivity factor together will decide which order bids will be cleared.
  - Bids from FSPs calculated in step 3.3.
  - SRA parameters. The LFM market-clearing will run for each SRA parameter and scenario defined in step 2 of the quantitative SRA process.

- **Post-evaluation (Step 3.5):** In addition to previous steps, the EUniversal SRA simulation approach includes an ex-post validation process to ensure that the clearing solution does not violate the limits exposed by the DSO. Note that this step is necessary due to the incomplete grid modelling considered in the LFM clearing. A complete AC OPF market clearing would not require this step. However, only a DSO would be able to do so; an independent LFM operator would not have this possibility due to grid data access constraints. This is why the SRA (and demo implementations) are based on sensitivity factors and a post-evaluation is needed. Moreover, the results of this step are useful for making comparisons between KPIs calculated before and after the flexibility procurement.

– **KPIs calculation (Step 4):** The EUniversal Deliverable 6.2 [13] identified and defined three types of KPIs for EUniversal, namely Project KPIs, Demo common KPIs, and Demo specific KPIs. Among these indicators, a set of KPIs was selected for the quantitative SRA based on the information provided in the KPI definition templates of D6.2 and the following criteria: i) KPIs related to BUCs of Table 1.1 whose calculations allow quantitative evaluations and comparisons (therefore, KPIs of the BUCs selected for only Qualitative SRA were excluded), ii) KPIs whose formulations are based on input data obtained from simulations, ii) Project level KPIs that were assigned as part of the SRA according to WP6 (EU_KPI_1, EU_KPI_2), the results of these KPIs are included in Section 2.5 of this report. Table 2.2 summarizes the selected KPIs, where their domains and link with the BUCs are detailed.

Table 2.2 EUniversal KPIs to consider for the quantitative SRA

KPI ID	KPI Name	KPI Domain	PL demo	DE demo	PT demo
CM_KPI_4	Avoided Restrictions	Technical	✓	✓	✓
DE_KPI_01	Cost of flexibility procurement	Economic	✓	✓	✓
PT_KPI_03	Avoided CO2 emissions from increased RES and DER hosting capacity	Environmental			✓
EU_KPI_1*	Increased RES and DER hosting capacity	Technical	✓	✓	✓
EU_KPI_2*	Increase of energy storage solutions penetration	Technical	✓	✓	✓

** Results of these project level KPIs are included in Section 2.5 of this report.*

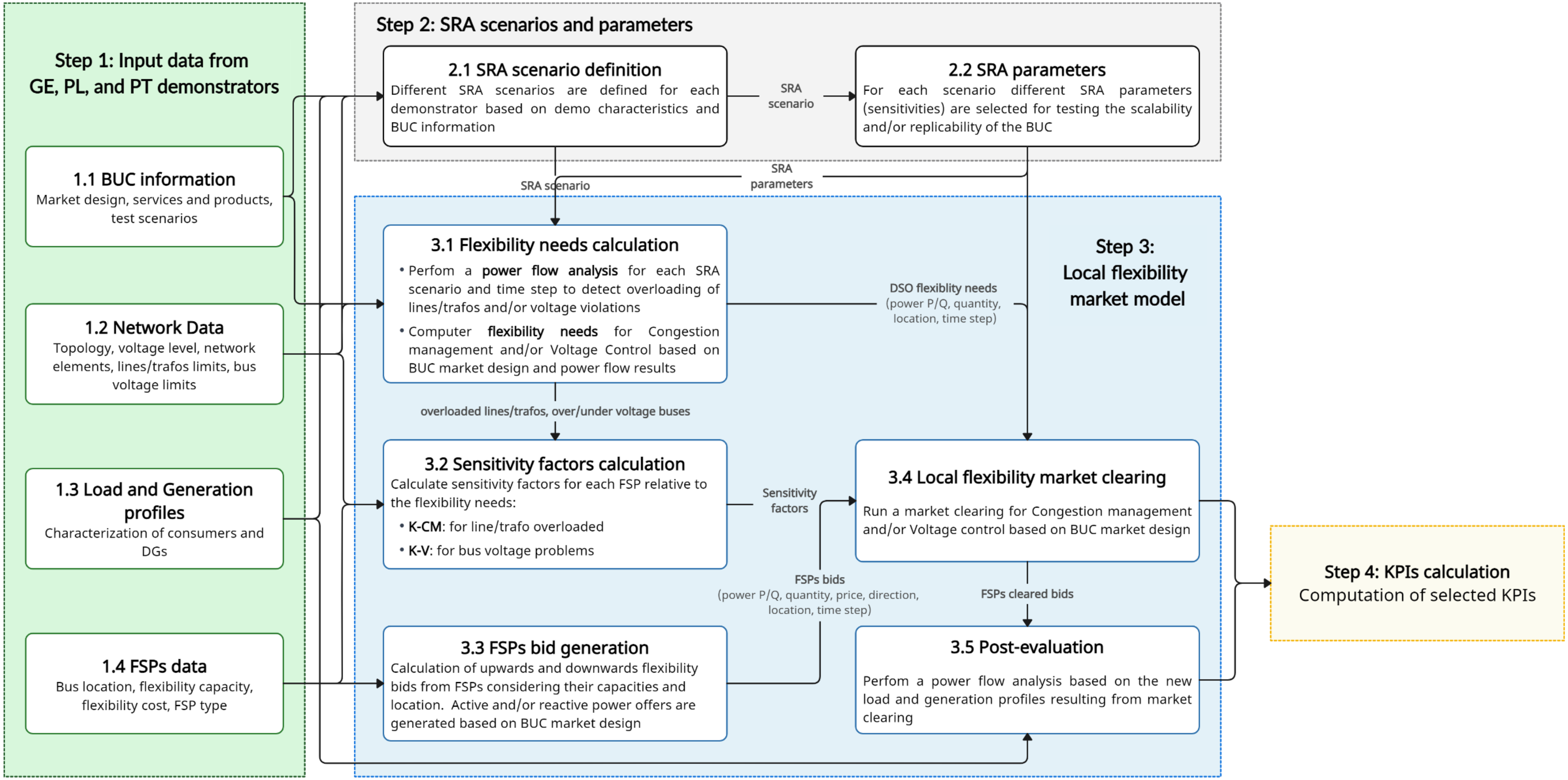


Figure 2.1 Quantitative SRA modeling and simulation process

2.2 Polish demonstrator quantitative SRA

This subsection aims to present and analyze the quantitative SRA results of the Polish demonstrator, with a specific focus on the PL-NET1-MV demo site. The selection of this demo site was determined earlier in the chapter, as explained in the EUniversal SRA approach (refer to Table 2.1). It is important to note that the content of this subsection follows the four steps proposed in the quantitative SRA methodology, providing details of the input data, SRA scenarios, LFM model, and KPIs results.

2.2.1 SRA: PL-NET1-MV

2.2.1.1 Step 1: Input data

a) Network characteristics and load and generation profiles

Table 2.3 summarizes the input data from the PL-NET1-MV demo site. A synthetic grid was built with similar characteristics to the real one using the information provided in D9.1 [4], the resulting MV synthetic grid consists of three MV feeders (15 kV) that start from two 110/30-15 kV transformers. Regarding the network elements, this grid consists of 22 buses, 20 lines, 8 aggregated load points, 7 distributed generators (4 WP generators, 2 CHP, 1 Biogas plants), and 1 energy storage.

Table 2.3 Polish demo site considered in the EUniversal SRA

Network ID	**PL-NET1-MV**
Network modelling	Synthetic grid
Grid level	MV grid 110/30-15 kV Lines R/X ratio: 1.5965
Network elements	22 buses, 20 lines, 2 HV/MV transformers, 8 load points (Aggregated MV loads), 7 DGs (WP, CHP, and Biogas), 1 storage.
Load and Generation profiles	**Daily profiles (24 hours)** Load profiles based on D9.1 [4]: max and min load demand days in 2016. Generation profiles: Wind power [14], Biogas and CHP plants based on their annual capacity MWh and capacity factors.
FSPs	Selection of FSPs based on D6.3 information: 6 FSPs (generation and storage)

Concerning the load and generation profiles, the year 2016 serves as the base year. D9.1 provides information about the hourly load consumption for days of maximum (08-01-2016) and minimum (08-05-2016) consumption. Thus, they were selected as representative days for the SRA. Figure 2.2 shows the total active power consumption profiles for the representative days. On the other hand, WP (wind power) generation profiles were built for the two representative days using the location, capacities of wind generators, and the normalized production profiles from [14]. Furthermore, for the two CHP generators an annual capacity of 48180 MWh and a capacity factor of 78% were considered, and for the biogas plant we consider an annual capacity of 7008 MWh and a capacity factor of 65%. Figure 2.3 depicts the total generation profiles for the two representative days.

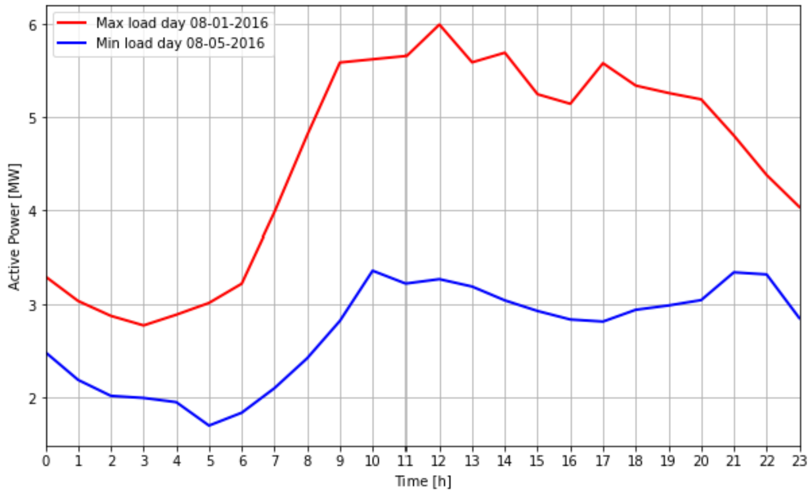


Figure 2.2 Total Active Power Consumption Max and Min load days

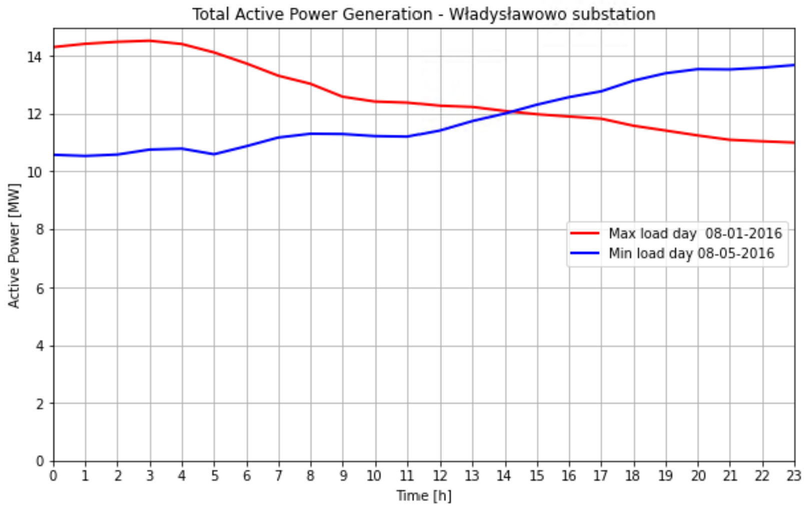


Figure 2.3 Total Active Power Generation Max and Min load days

b) FSPs characteristics

Table 2.4 describes the FSPs considered in the Polish demo. The information related to the FSPs type and capacity was obtained from D9.1 [4]. The flexibility costs for active power were obtained from the Picloflex platform [15], and the reactive power bids cost was considered to be 5% of the active power cost assuming that the reactive power costs are due to the internal active power losses caused for the keeping the established reactive power set-point. [16]–[18]. Moreover, it should be noted that most of the FSPs offer upward and downward flexibility (active and reactive) except wind generators that don't offer active upward flexibility. For the SRA, we consider that each FSP has an available flexibility of 5% of its maximum capacity (base case). Based on the capability analysis of DERs operating curves, the value of 5% is also considered for reactive power bids [16].

Table 2.4 FSPs Characteristics, Polish demonstrator

<table>
<tr><th>FSP ID</th><th>Bus ID</th><th>FSP type</th><th>Nominal capacity [MVA]</th><th>Active power upward capacity [%]</th><th>Active power down ward capacit y [%]</th><th>Active power upward cost [EU/MWh]</th><th>Active power downwar d cost [EU/MW h]</th><th>Reactive power upward capacity [%]</th><th>React. power down ward capacit y [%]</th><th>React. power upwar d cost [EU/M Wh]</th><th>Reactive power downward cost [EU/MWh]</th></tr>
<tr><td>fsp0</td><td>12</td><td rowspan="5">generation</td><td>0.8</td><td>5 %</td><td rowspan="6">5%</td><td>39.99</td><td>39.62</td><td rowspan="6">5 %</td><td rowspan="6">5 %</td><td>2</td><td>1.98</td></tr>
<tr><td>fsp1</td><td>3</td><td>0.6</td><td rowspan="4">0 %</td><td>39.41</td><td>39.97</td><td>1.97</td><td>2</td></tr>
<tr><td>fsp2</td><td>4</td><td>0.6</td><td>39.58</td><td>39.91</td><td>1.98</td><td>2</td></tr>
<tr><td>fsp3</td><td>5</td><td>3.2</td><td>39.89</td><td>40.1</td><td>1.99</td><td>2.01</td></tr>
<tr><td>fsp4</td><td>10</td><td>1.6</td><td>40</td><td>40.01</td><td>2</td><td>2</td></tr>
<tr><td>fsp5</td><td>9</td><td>storage</td><td>0.75</td><td>5 %</td><td>39.57</td><td>39.6</td><td>1.98</td><td>1.98</td></tr>
</table>

2.2.1.2 Step 2: SRA scenarios

For the quantitative SRA of the Polish demonstrator, different scenarios are tested according to Table 2.5. This table also summarizes the SRA parameters and the KPIs to be calculated for each scenario. Two scenarios are defined. Scenario 0 analyzes the PL-NET1-MV distribution network under the conditions of the two representative days previously selected, Scenario 0.A (day of maximum load consumption) and Scenario 0.B (day of minimum load consumption). On the other hand, due to the large share of distributed generation in this demo site, Scenario 1 examines the congestion events in the network under the same representative day as Scenario 0.A, but the total generation of the network is increased by a factor of 2. Scenario 0.A was selected because this scenario's net generation is higher than Scenario 0.B. The quantitative SRA methodology is applied for each of these scenarios, and the results are further analyzed in the following subsections.

Table 2.5 SRA scenarios for the Polish demonstrator

<table>
<tr><th>Scenario ID</th><th>Description</th><th>SRA parameters</th><th>KPIs</th></tr>
<tr><td rowspan="2">Scenario 0</td><td>A: Initial profiles considering maximum load consumption day (08-01-2016)</td><td colspan="2" rowspan="2">No congested elements</td></tr>
<tr><td>B: Initial profiles considering minimum load consumption day (08-05-2016)</td></tr>
<tr><td>Scenario 1</td><td>Scenario 0.A + Increase total generation by a factor of 2.</td><td>Generation scaling-up,
FSPs bid size,
Storage capacity,
Limits of bus voltage magnitude.</td><td>CM_KPI_4: Avoided restrictions
EU_KPI_1: Increased RES and DER hosting capacity
EU_KPI_2: Increase of energy storage solutions penetration</td></tr>
</table>

2.2.1.3 Step 3: LFM model

a) SRA Scenario 0

The SRA methodology described in Subchapter 2.1 is applied for Scenario 0, therefore, this section describes the results of the required steps considered for the methodology:

- **Flexibility needs calculation (Step 3.1):** The first step is to perform a power flow analysis for 24 hours (market horizon) to identify possible constraints in the grid. Network data and load and generation profiles described in section 2.2.1.1 are considered. Figure 2.4, Figure 2.5 and Figure 2.6 show power results for the maximum load representative day (Scenario 0.A). Furthermore, Figure 2.7, Figure 2.8, and Figure 2.9, present the equivalent results for the minimum load representative day (Scenario 0.B). These results show that congestion problems (lines and transformers overloading events) do not occur under Scenario 0. However, for the maximum load representative day, as shown in Figure 2.6, there are some buses with voltage magnitude under 0.95 p.u. between 9h00 to 22h00.

  It is important to note that the resulting flexibility needs are focused only on voltage control, which is not in line with the objective of the BUCs in the Polish demonstrator, to test a LFM for both congestion management and voltage control services. Therefore, it becomes necessary to define a new scenario that aligns with this objective, which is analyzed in the following subsection.

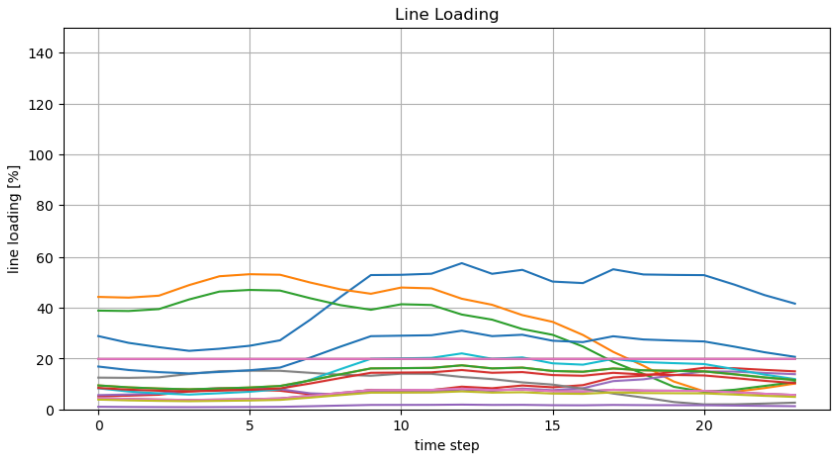


Figure 2.4 Lines loading [%], Scenario 0, max load day, PL-NET1-MV

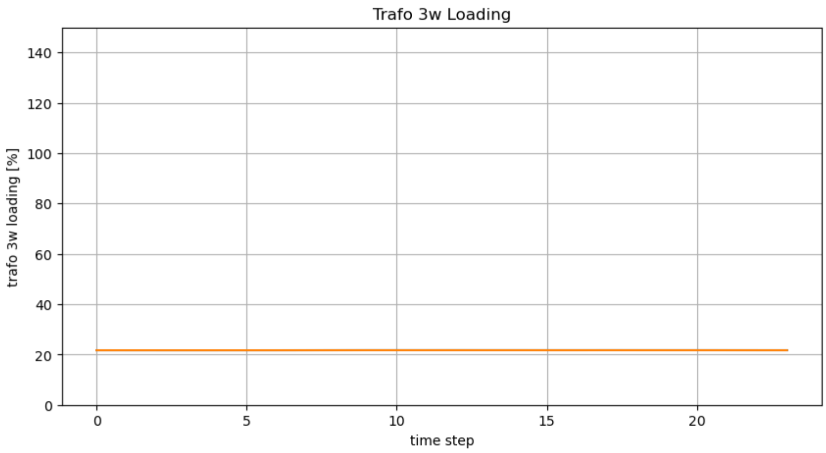


Figure 2.5 Transformer loading [%], Scenario 0, max load day, PL-NET1-MV

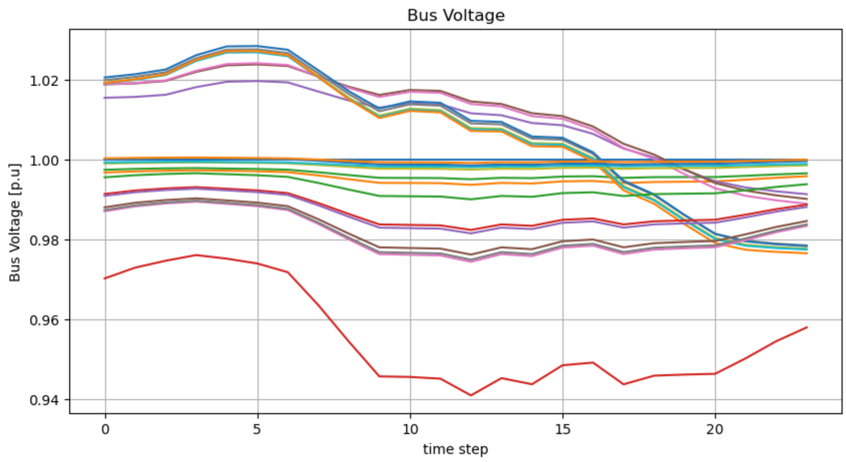


Figure 2.6 Bus Voltage [p.u.] for the Scenario 0, max load day, PL-NET1-MV

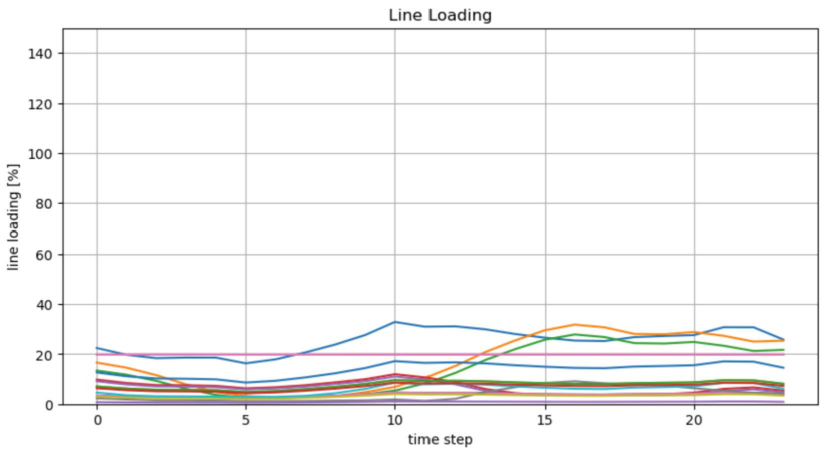


Figure 2.7 Line loading [%] for the Scenario 0, min load day, PL-NET1-MV

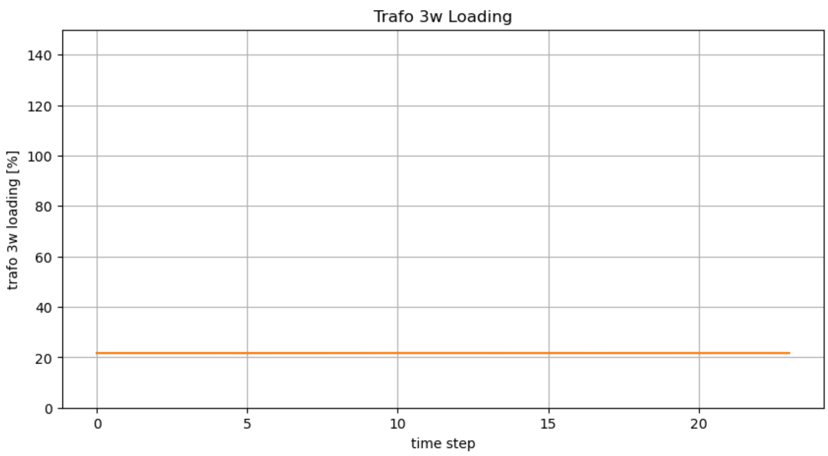


Figure 2.8 Transformer loading [%] for the Scenario 0, min load day, PL-NET1-MV

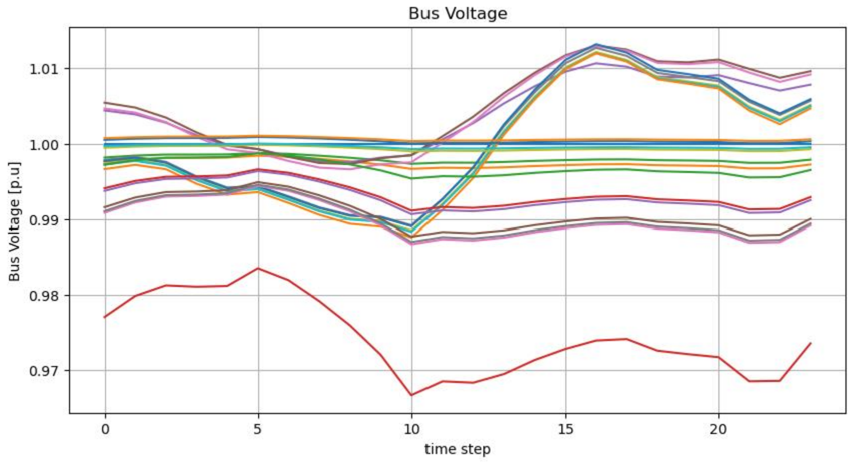


Figure 2.9 Bus Voltage [p.u.] for the Scenario 0, min load day, PL-NET1-MV

b) SRA Scenario 1

This section presents the results obtained by applying the SRA methodology outlined in Table 2.5 for Scenario 1. This scenario examines the congestion events in the network under the same representative day of Scenario 0.A, but the total generation of the network is increased by a factor of 2. The results of the SRA methodology are further described below.

- **Flexibility needs calculation (Step 3.1):** Considering the new generation profiles, a power flow analysis is run for 24 hours to identify potential constraints. Figure 2.10, Figure 2.11, and Figure 2.12 show the results for lines loading, transformers loading, and bus voltage magnitude, respectively. From Figure 2.10, we notice that two lines (L1 and L2) are congested, i.e., they exceed the maximum overload limit (100%). Similarly, from Figure 2.12, we can observe that some buses have undervoltage values (below 0.95 p.u.) and overvoltage values (above 1.05 p.u.). Furthermore, it is important to highlight that there are no congestion problems in the transformers, see Figure 2.11.

  Considering power flow results, the corresponding flexibility needs are computed. Table 2.6 summarizes scenario 1 flexibility needs and network issues associated with congestion management and voltage control, resulting in 16 congestion problems and 86 voltage violations. These values are determined by considering the number of congested elements multiplied by the hours when these problems occur. Furthermore, bus voltage violations are shown in detail in Figure 2.13, where we can observe that only bus 3 presents undervoltage problems, while overvoltage problems occur on several buses in this scenario, being more critical for bus 10 during 5 am and 6 am.

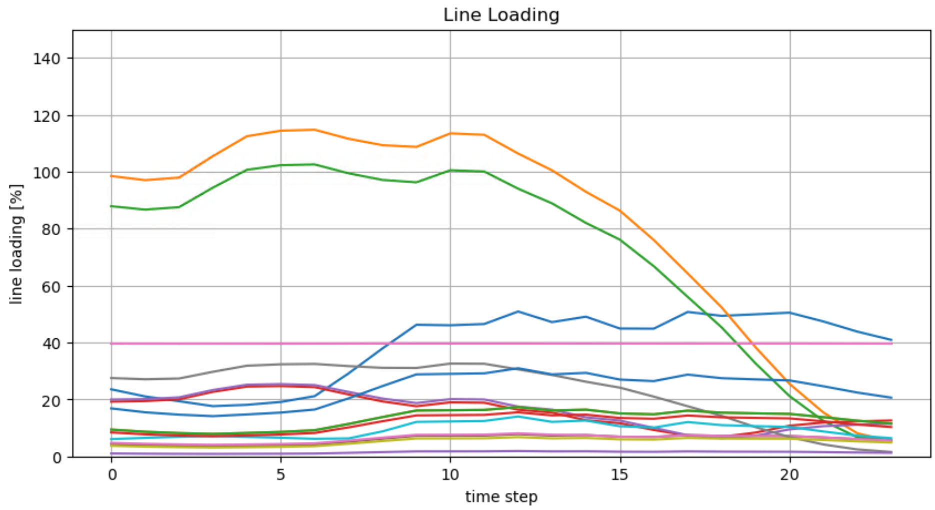


Figure 2.10 Line loading [%] for the Scenario 1, PL-NET1-MV

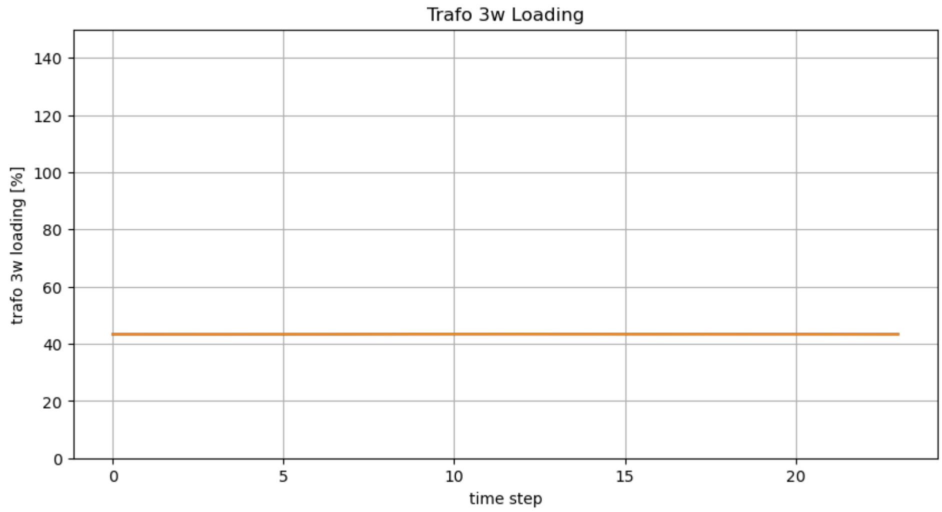


Figure 2.11 Transformer loading [%] for the Scenario 1, PL-NET1-MV

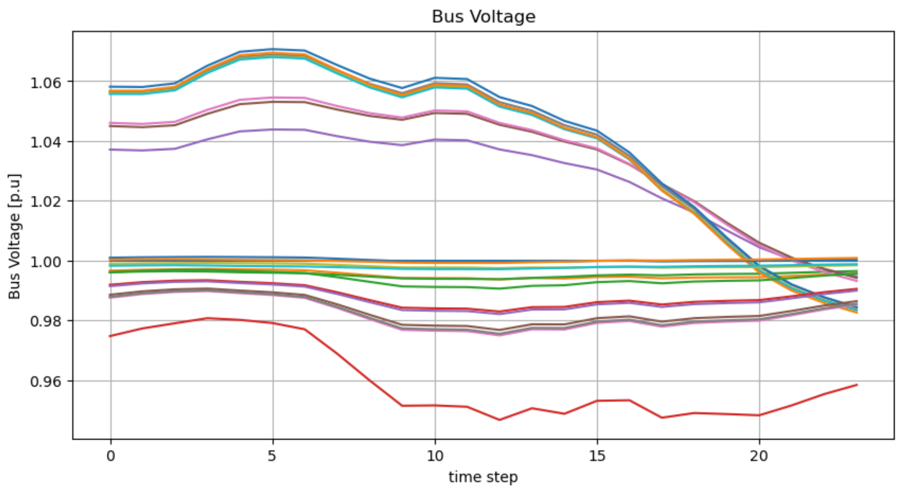


Figure 2.12 Bus Voltage [p.u.] for the Scenario 1, PL-NET1-MV

Table 2.6 Summary of Flexibility Needs for PL-NET1-MV

Congestion management and voltage control flexibility needs	Value
Congested lines and/or transformers	Lines # 1 and #2
Total congestion problems (congested elements by hours)	16
Overvoltage problems (bus with overvoltage by hours)	80
Undervoltage problems (bus with undervoltage by hours)	6

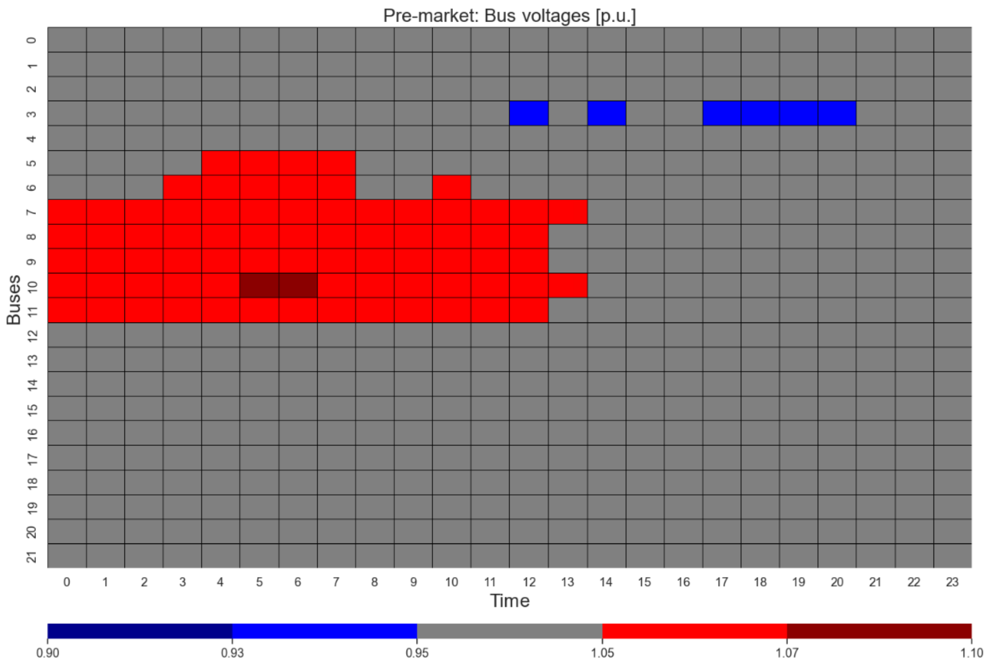


Figure 2.13 Summary of Bus Voltage Violations [p.u.] for Scenario 1, PL-NET1-MV

- **Sensitivity factors calculation (Step 3.2):** In this step, sensitivity factors are computed for each FSP participating in the local market relative to the flexibility needs obtained in the previous step. As stated in Section 2.1, sensitivity factors for congestion management describe how the apparent power of a congested line or transformer could be impacted by variations in the active (dS/dP) or reactive (dS/dQ) power provided by FSPs. For voltage control, sensitivity factors indicate how the voltage at a specific node could be impacted by variations in active (dV/dP) or reactive (dV/dQ) power provided by the FSP. Table 2.7 and Table 2.8 summarize the resulting sensitivity factors for both services. It should be emphasized that the sensitivity factors have been computed for each hour of study (hours with congestion events in lines, transformers, or buses). For simplicity, the values shown in both tables correspond to the mean ± standard deviation of all hourly values obtained.

  Regarding congestion management, Table 2.7 indicates that changes in active power (P) and reactive power (Q) in FSPs 2, 3, 4, and 5 directly impact the apparent power (S) of line L1 with factors very close to unity in the case of P (column 1), and with smaller factors in the case of Q (column 2). By contrast, FSPs 0 and 1 have no impact at all. For line L2, we can observe that P (column 3) and Q (column 4) variations in FSPs 3, 4, and 5 have a direct effect on the apparent power of this line, while the corresponding variations in FSPs 0, 1 and 2 do not exert any influence. The positive sign of the sensitivity factors implies a direct relationship, which means that an increase in P or Q in FSP results in a rise in the S value of the congested element. A negative sign implies an opposite behavior.

With regards to voltage control, although Figure 2.13 illustrates voltage issues across multiple nodes, Table 2.8 provides a summary of computed sensitivity factors for buses with extreme values, i.e., bus 3 (undervoltage) and bus 10 (overvoltage). It can be observed that both active and reactive power injections from FSP 3 impact node 3, while the rest of FSPs affect node 10.

Table 2.7 Sensitivity factors for congestion management, Scenario 1, PL-NET1-MV ([5])

FSP ID	FSP type	Sensitivity factors L1 dS/dP	Sensitivity factors L1 dS/dQ	Sensitivity factors L2 dS/dP	Sensitivity factors L2 dS/dQ
fsp0	generation	0	0	0	0
fsp1		0	0	0	0
fsp2		1.00 ± 4.6e-3	-0.087 ± 3.4e-3	0	0
fsp3		0.98 ± 2.2e-3	-0.086 ± 3.4e-3	0.99 ± 6.1e-3	-0.069 ± 3.3e-3
fsp4		0.95 ± 7.4e-3	-0.080 ± 3.3e-3	0.97 ± 4.6e-3	-0.062 ± 4.3e-3
fsp5	storage	0.96 ± 6.9e-3	-0.080 ± 3.2e-3	0.97 ± 4.2e-3	-0.062 ± 4.3e-3

Table 2.8 Sensitivity factors for voltage control, Scenario 1, PL-NET1-MV ([6])

FSP ID	FSP type	Sensitivity factors Bus 3 (worst bus - undervoltage) dV/dP	Sensitivity factors Bus 3 (worst bus - undervoltage) dV/dQ	Sensitivity factors Bus 10 (worst bus - overvoltage) dV/dP	Sensitivity factors Bus 10 (worst bus - overvoltage) dV/dQ
fsp0	generation	0	0	4.9e-03 ± 1.8e-18	4.9e-03 ± 5.4e-06
fsp1		1.9e-02 ± 3.5e-18	1.8e-02 ± 4.1e-06	0	0
fsp2		0	0	1.2e-02 ± 5.3e-18	1.2e-02 ± 8.5e-06
fsp3		0	0	1.3e-02 ± 1.7e-18	1.3e-02 ± 9.1e-06
fsp4		0	0	2.6e-02 ± 7.1e-18	2.7e-02 ± 2.4e-06
fsp5	storage	0	0	2.5e-02 ± 4.9e-5	2.6e-02 ± 0.4e-5

[5] Sensitivity factors have been computed for each hour of study. For simplicity, the reported values correspond to the mean ± standard deviation of the all hourly values obtained.

[6] Sensitivity factors have been computed for each hour of study. For simplicity, the reported values correspond to the mean ± standard deviation of the all hourly values obtained.

- **FSP's bid generation (Step 3.3):** This step computes the flexibility limit that each FSP can provide, both downward and upward, for active and reactive power, based on FSPs characteristics provided in Table 2.4.

- **Local flexibility market-clearing (Step 3.4) and post-evaluation (Step 3.5):** In step 3.4, a local flexibility market-clearing is carried out to solve the criticalities identified in step 3.1 using the most efficient flexibility bids from FSPs (step 3.3) at minimum cost. The LFM clearing considers the sensitivities factors computed in step 3.2 as a representation of the network constraints. The LFM model implemented for the SRA for the Polish demo SRA test the scalability and replicability performance of the LFM models of the selected BUCs (BUC LFM models), and other additional LFM models are considered for further analysis.

To evaluate the SRA performance of scenario 1, sensitivities are applied to three key SRA parameters presented in Table 2.9. The first parameter involves the modification of bus voltage limits consider in the model. The second parameter entails increasing the upwards and downwards flexibility capacity of the FSPs. Lastly, changes in the storage capacity of FSP5 were considered as the third parameter. Furthermore, it should be emphasized that a cost of 6260 (EUR/MWh) is considered for the $VOLL$ parameter in the Polish demonstrator according to the report in [19].

Table 2.9 Sensitivities to the SRA parameters for scalability, Scenario 1, PL-NET1-MV

Parameter	Parameter description	Sensitivity Range
M01 - M02	Limits of maximum and minimum permissible voltage levels for buses	$M0x = [v_{min}, v_{max}]$ $M01 = [0.95, 1.05]$ $M02 = [0.93, 1.07]$
F01 – F05	Increase in available flexibility from FSPs	*F0x* = [5%, 10%, 15%, 20%, 25%]
SK01 – SK02	Increase in storage capacity of FSP 5.	*SK0x* = [Nominal Capacity, Twice Nominal Capacity]

Table 2.10 and Table 2.11 summarize the results obtained after the market clearing for each scenario evaluated, considering the sensitivities from Table 2.9. According to Table 2.1, the main BUC LFM models required for the Polish Network involve Congestion Management and Voltage Control utilizing active power (CMVCP) and reactive power (CMVCQ). In both tables, the cost of the Objective Function equals the sum of the costs of the total active and reactive power FSP's bids cleared in the market plus the cost of the auxiliary variables Alpha and Beta, which implies that the model has been satisfactorily solved. Alpha represents the cost of the flexibility not supplied by the Voltage Control component, while Beta corresponds to the cost of the flexibility not supplied by the Congestion Management component[7]. As the capacities of the FSPs increase (from F01 to F05), the associated costs of Alpha and Beta decrease. Given the high costs attributed to these factors, their reduction aligns with the model's objective

[7] A comprehensive description of Alpha and Beta can be found in the LFM formulation of Annex II.

to minimize total costs. Furthermore, it can be noted that under conditions with lower voltage boundary constraints (specifically M02 in comparison to M01), the cost of Alpha becomes zero.

It should be noted that in the case of CMVCP, there are no costs associated with reactive power. Similarly, in the case of CMVCQ, the active power cost column is empty. This logical result arises from the fact that these types of offers compete exclusively in their respective markets. Additionally, Table 2.12 presents results obtained by considering a LFM models for Congestion Management and Voltage Control, where both active and reactive power are simultaneously considered. It can be seen that this model achieves a more significant reduction in total costs compared to the two previous cases, potentially due to a lower unsupplied flexibility. The observed trend of cost reduction is consistent with previous cases, and there are costs associated with both active and reactive power that have been matched in the market.

Table 2.10 Summary of costs resulting from the market clearing for congestion management and voltage control with active power, Scenario 1, PL-NET1-MV

Scenario	Objective Value [EUR]	Beta Cost [EUR]	Alpha Cost [EUR]	Total Active Power [MW]	Active Power Cost [EUR]	Total Reactive Power [MVAR]	Reactive Power Cost [EUR]
CMVCP_S01_M01_F01_SK01	199.408,64	20.643,01	178.528,09	5,94	237,54	-	-
CMVCP_S01_M01_F02_SK01	134.017,94	10.353,34	123.321,04	8,59	343,55	-	-
CMVCP_S01_M01_F03_SK01	82.426,60	2.945,71	79.047,59	10,83	433,30	-	-
CMVCP_S01_M01_F04_SK01	53.819,16	-	53.334,36	12,12	484,80	-	-
CMVCP_S01_M01_F05_SK01	36.101,38	-	35.593,22	12,70	508,16	-	-
CMVCP_S01_M01_F01_SK02	199.408,64	20.643,01	178.528,09	5,94	237,54	-	-
CMVCP_S01_M01_F02_SK02	134.017,94	10.353,34	123.321,04	8,59	343,55	-	-
CMVCP_S01_M01_F03_SK02	82.426,60	2.945,71	79.047,59	10,83	433,30	-	-
CMVCP_S01_M01_F04_SK02	53.819,16	-	53.334,36	12,12	484,80	-	-
CMVCP_S01_M01_F05_SK02	36.101,38	-	35.593,22	12,70	508,16	-	-
CMVCP_S01_M02_F01_SK01	19.442,44	19.289,41	-	3,82	153,03	-	-
CMVCP_S01_M02_F02_SK01	9.288,51	9.071,70	-	5,42	216,81	-	-
CMVCP_S01_M02_F03_SK01	2.429,27	2.167,72	-	6,53	261,55	-	-
CMVCP_S01_M02_F04_SK01	274,83	-	-	6,86	274,83	-	-
CMVCP_S01_M02_F05_SK01	273,93	-	-	6,84	273,93	-	-
CMVCP_S01_M02_F01_SK02	18.992,83	18.839,67	-	3,83	153,17	-	-
CMVCP_S01_M02_F02_SK02	9.288,51	9.071,70	-	5,42	216,81	-	-
CMVCP_S01_M02_F03_SK02	2.429,27	2.167,72	-	6,53	261,55	-	-
CMVCP_S01_M02_F04_SK02	274,83	-	-	6,86	274,83	-	-
CMVCP_S01_M02_F05_SK02	273,93	-	-	6,84	273,93	-	-

Table 2.11 Summary of costs resulting from the market clearing for congestion Management and voltage control with reactive power, Scenario 1, PL-NET1-MV

Scenario	Objective Value [EUR]	Beta Cost [EUR]	Alpha Cost [EUR]	Total Active Power [MW]	Active Power Cost [EUR]	Total Reactive Power [MVAR]	Reactive Power Cost [EUR]
CMVCQ_S01_M01_F01_SK01	203.946,90	54.231,60	149.700,02	-	-	7,64	15,28
CMVCQ_S01_M01_F02_SK01	142.194,59	56.205,28	85.967,35	-	-	10,98	21,95
CMVCQ_S01_M01_F03_SK01	105.827,32	57.274,95	48.525,16	-	-	13,62	27,21
CMVCQ_S01_M01_F04_SK01	82.914,20	57.420,80	25.462,57	-	-	15,45	30,84
CMVCQ_S01_M01_F05_SK01	67.756,68	56.948,38	10.773,85	-	-	17,27	34,45
CMVCQ_S01_M01_F01_SK02	188.004,30	54.578,21	133.409,88	-	-	8,12	16,21
CMVCQ_S01_M01_F02_SK02	126.163,38	56.524,93	69.615,08	-	-	11,70	23,37
CMVCQ_S01_M01_F03_SK02	93.301,49	57.120,50	36.152,82	-	-	14,12	28,17
CMVCQ_S01_M01_F04_SK02	73.326,04	56.705,12	16.588,63	-	-	16,21	32,30
CMVCQ_S01_M01_F05_SK02	64.869,78	55.813,20	9.018,56	-	-	19,09	38,02
CMVCQ_S01_M02_F01_SK01	49.288,48	49.275,99	-	-	-	6,29	12,49
CMVCQ_S01_M02_F02_SK01	48.525,56	48.508,45	-	-	-	8,60	17,11
CMVCQ_S01_M02_F03_SK01	47.830,81	47.808,16	-	-	-	11,39	22,65
CMVCQ_S01_M02_F04_SK01	47.136,22	47.108,02	-	-	-	14,18	28,20
CMVCQ_S01_M02_F05_SK01	46.462,34	46.428,92	-	-	-	16,79	33,41
CMVCQ_S01_M02_F01_SK02	49.124,10	49.111,72	-	-	-	6,23	12,38
CMVCQ_S01_M02_F02_SK02	48.381,49	48.363,15	-	-	-	9,22	18,34
CMVCQ_S01_M02_F03_SK02	47.666,42	47.642,56	-	-	-	11,99	23,86
CMVCQ_S01_M02_F04_SK02	47.008,16	46.979,37	-	-	-	14,48	28,80
CMVCQ_S01_M02_F05_SK02	46.352,48	46.318,11	-	-	-	17,28	34,36

Table 2.12 Summary of resulting costs from the market clearing for congestion management and voltage control with active and reactive power, Scenario 1, PL-NET1-MV

Scenario	Objective Value [EUR]	Beta Cost [EUR]	Alpha Cost [EUR]	Total Active Power [MW]	Active Power Cost [EUR]	Total Reactive Power [MVAR]	Reactive Power Cost [EUR]
CMVCPQ_S01_M01_F01_SK01	83.888,92	22.442,24	61.214,86	5,45	217,92	6,95	13,89
CMVCPQ_S01_M01_F02_SK01	33.847,13	11.622,47	21.947,36	6,50	259,83	8,75	17,48
CMVCPQ_S01_M01_F03_SK01	15.965,92	3.439,81	12.200,69	7,69	307,38	9,04	18,03
CMVCPQ_S01_M01_F04_SK01	10.931,29	0,36	10.609,63	7,74	309,58	5,89	11,73
CMVCPQ_S01_M01_F05_SK01	9.332,67	-	9.018,56	7,59	303,66	5,25	10,44
CMVCPQ_S01_M01_F01_SK02	77.166,21	22.531,57	54.410,27	5,24	209,47	7,46	14,90
CMVCPQ_S01_M01_F02_SK02	28.786,99	11.551,04	16.962,64	6,38	255,23	9,06	18,07
CMVCPQ_S01_M01_F03_SK02	15.810,43	3.289,29	12.200,69	7,56	302,56	8,98	17,89
CMVCPQ_S01_M01_F04_SK02	10.924,57	-	10.609,63	7,59	303,64	5,68	11,30
CMVCPQ_S01_M01_F05_SK02	9.332,51	-	9.018,56	7,59	303,57	5,22	10,38
CMVCPQ_S01_M02_F01_SK01	17.282,01	17.096,78	-	4,27	170,59	7,38	14,65
CMVCPQ_S01_M02_F02_SK01	7.466,18	7.223,19	-	5,67	226,85	8,12	16,14
CMVCPQ_S01_M02_F03_SK01	1.588,31	1.315,08	-	6,38	255,38	8,99	17,85

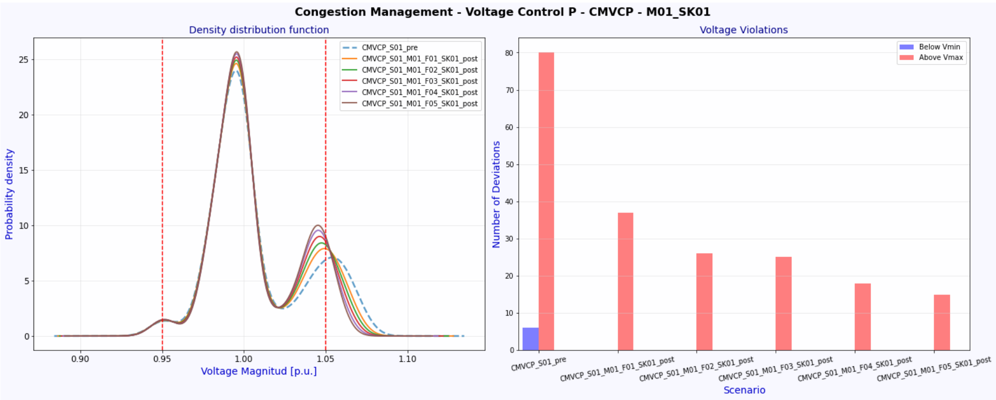
CMVCPQ_S01_M02_F04_SK01	264,39	-	-	6,24	249,78	7,35	14,61
CMVCPQ_S01_M02_F05_SK01	263,37	-	-	6,21	248,42	7,52	14,95
CMVCPQ_S01_M02_F01_SK02	16.926,58	16.742,87	-	4,26	170,17	6,82	13,55
CMVCPQ_S01_M02_F02_SK02	7.462,65	7.219,25	-	5,67	226,83	8,34	16,56
CMVCPQ_S01_M02_F03_SK02	1.588,15	1.314,86	-	6,38	255,38	9,02	17,91
CMVCPQ_S01_M02_F04_SK02	264,39	-	-	6,24	249,78	7,35	14,61
CMVCPQ_S01_M02_F05_SK02	263,37	-	-	6,21	248,42	7,52	14,95

As technical results, Figure 2.14, Figure 2.15, and Figure 2.16 show density plots of all bus voltages [p.u.], before (pre) and after (post) the market, for CMCVP, CMCVQ, and CMCVPQ, across each considered scenario. Moreover, the bar plots accompanying the density plots demonstrate the changes in voltage violations for each scenario. Similarly, Figure 2.17, Figure 2.18, and Figure 2.19 present density plots illustrating the load percentage of lines, while the corresponding bar graphs specifically highlight the lines experiencing congestion problems.

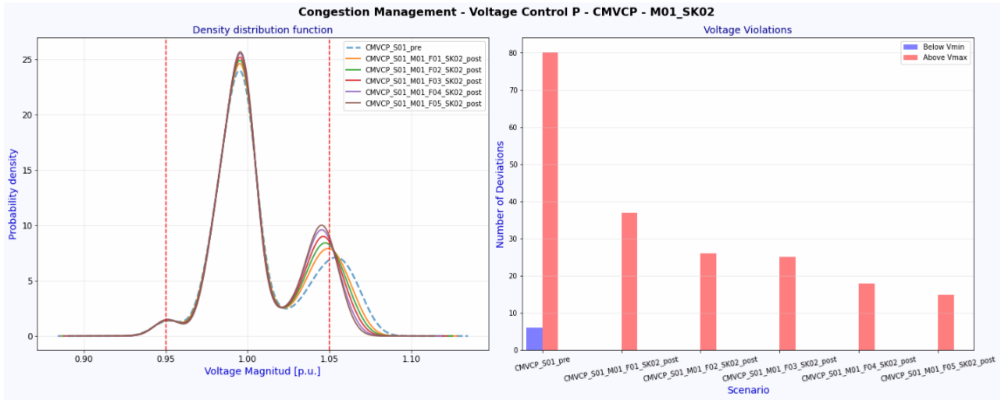
From the voltage density plots, it can be seen that as the size of the FSPs increase (from F01 to F05), bus voltages tend to converge within the voltage limits compared to the pre-market conditions. The bar plots show that in M01 cases, the overvoltage problems that were present before the market significantly decrease, while the undervoltage problems are effectively compensated through market mechanisms. Comparing the impacts of CMVCP, CMVCQ, and CMVCPQ model markets, for M01, it can be observed that the latter achieves a remarkable reduction in overvoltage problems as FSPs size increase. In the case of scenario M02, the market successfully resolves voltage problems across various sensitivities of F0x and SK0x. The market mechanisms prove effective in addressing voltage concerns under different conditions.

Similar behavior can be observed in the graphs depicting the lines, where the density plot moves closer to the maximum thermal limit as the size of the FSPs increase. Notably, the CMVCPQ market model consistently achieves better results compared to CMVCP and CMVCQ in terms of congestion management. Interestingly, when considering only the use of reactive power for congestion management, increasing the capacity of FSPs to provide reactive power does not seem to effectively solve congestion problems. In fact, congestion issues may even intensify. This suggests that the utilization of reactive power alone may not be sufficient to mitigate congestion effectively.

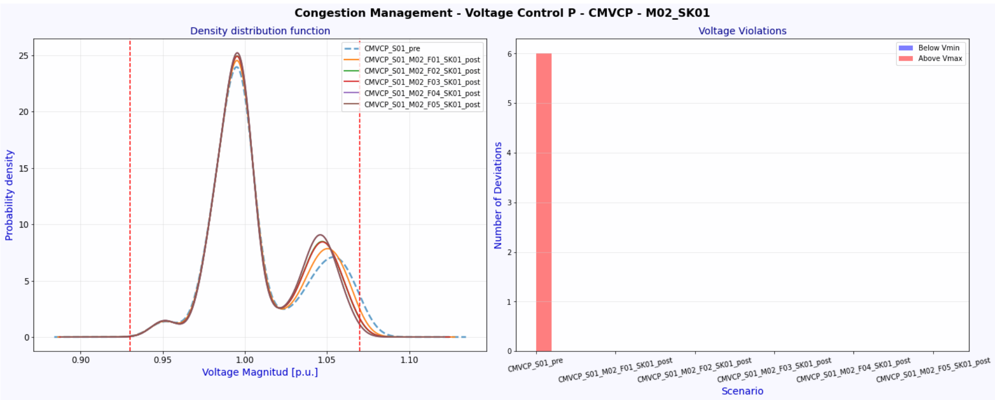
(a)



(c)



(b)



(d)

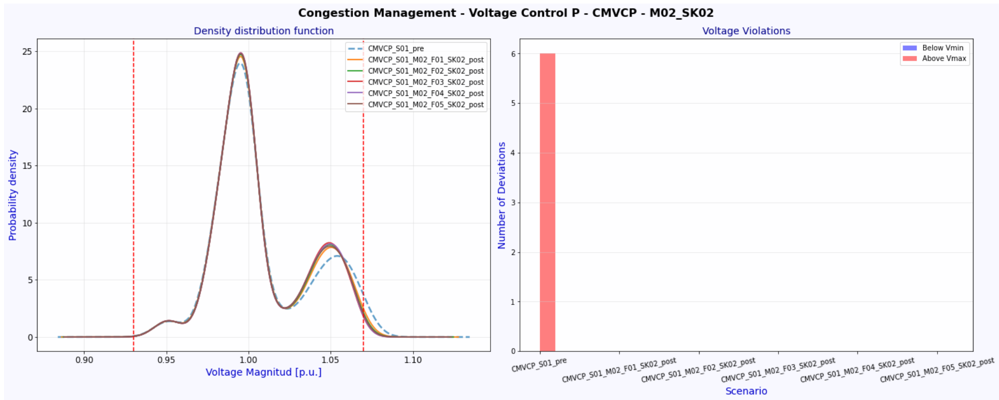
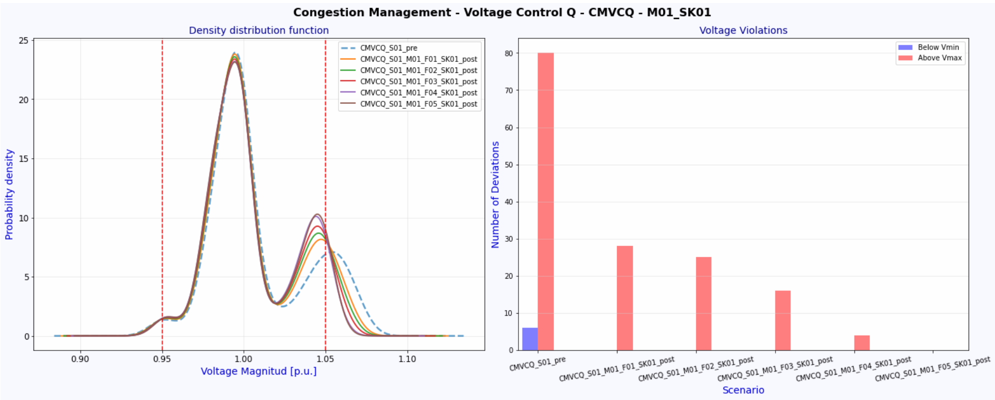
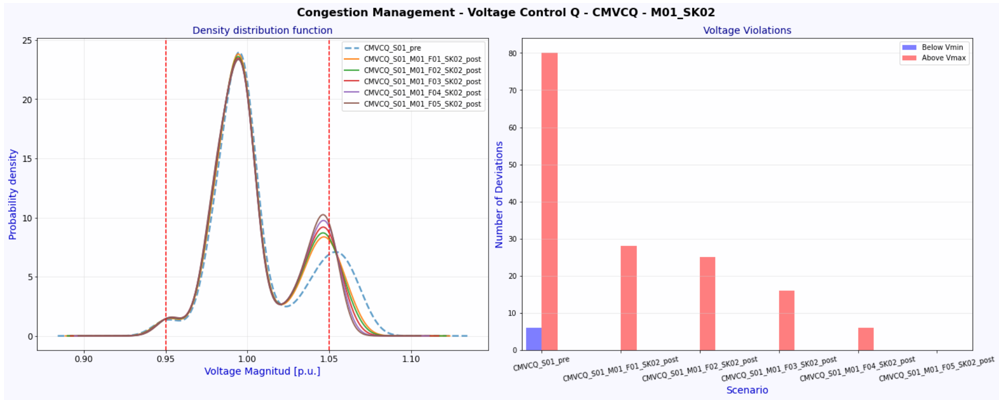


Figure 2.14 Density plots for Voltage Magnitude [p.u.] of all buses obtained from Congestion Management – Voltage Control with Active Power (a) Scenario M01-K01, (b) Scenario M02-K01, (c) Scenario M01-K02, (d) Scenario M02-K02. Scenario 1, PL-NET1-MV

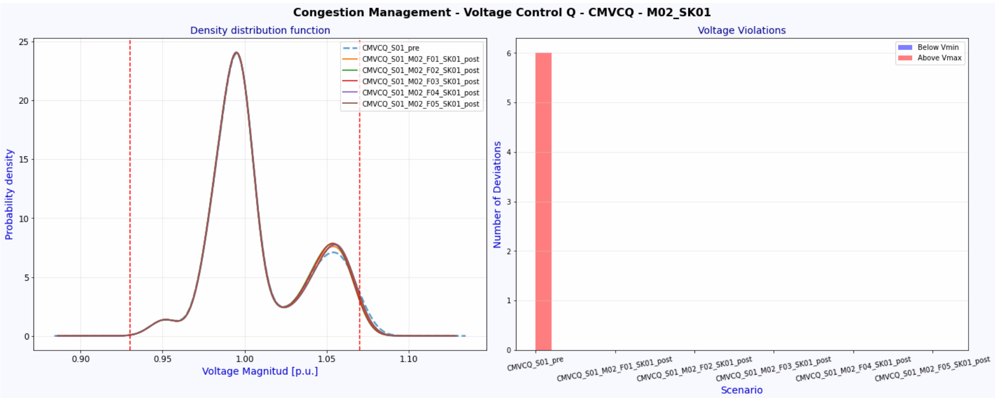
(a)



(c)



(b)



(d)

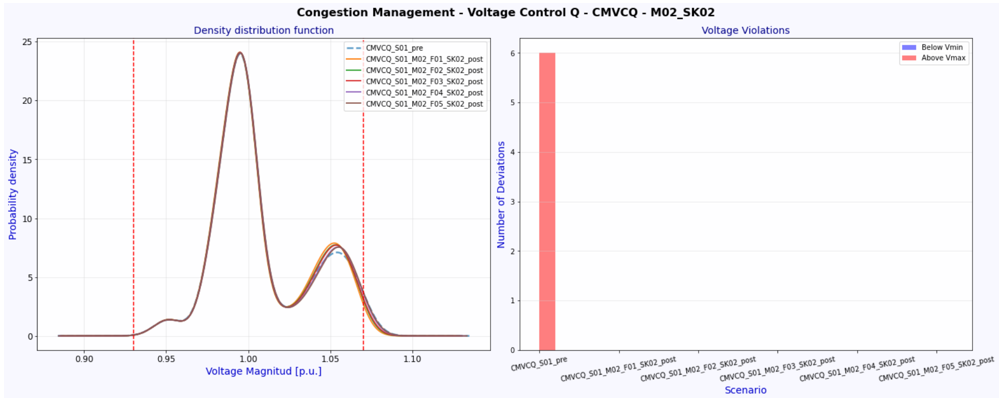


Figure 2.15 Density plots for Voltage Magnitude [p.u.] of all buses obtained from Congestion Management – Voltage Control with Reactive Power (a) Scenario M01-K01, (b) Scenario M02-K01, (c) Scenario M01-K02, (d) Scenario M02-K02. Scenario 1, PL-NET1-MV

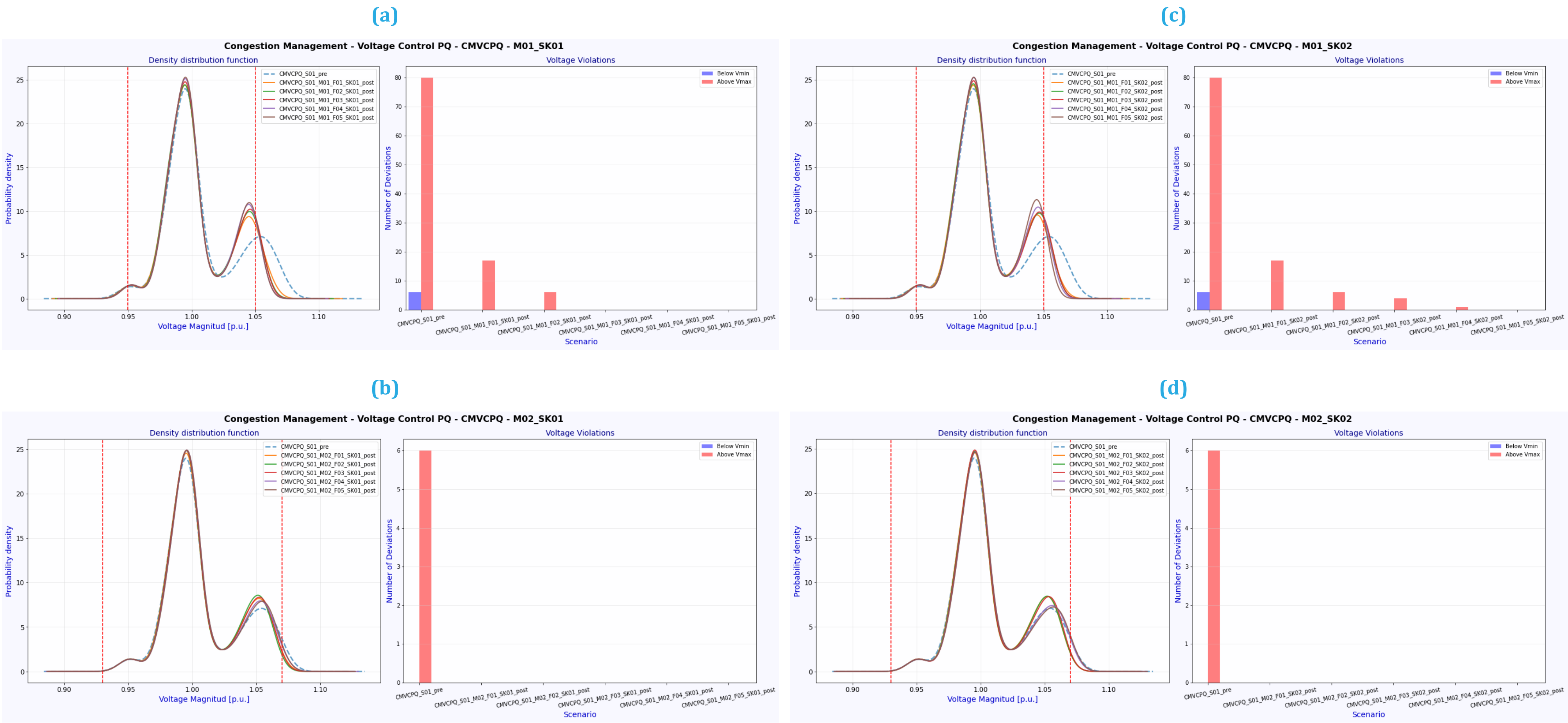


Figure 2.16 Density plots for Voltage Magnitude [p.u.] of all buses obtained from Congestion Management – Voltage Control with Active and Reactive Power (a) Scenario M01-K01, (b) Scenario M02-K01, (c) Scenario M01-K02, (d) Scenario M02-K02. Scenario 1, PL-NET1-MV

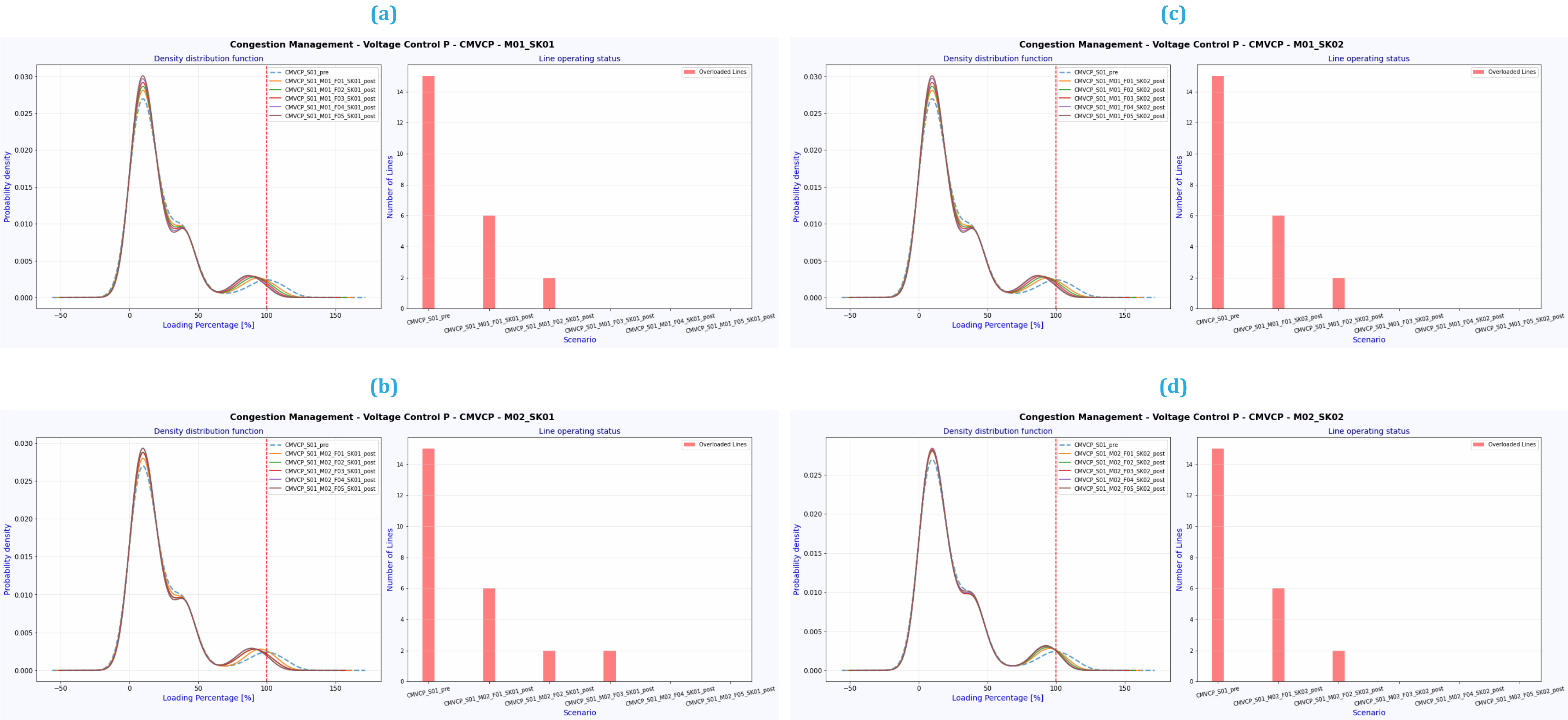
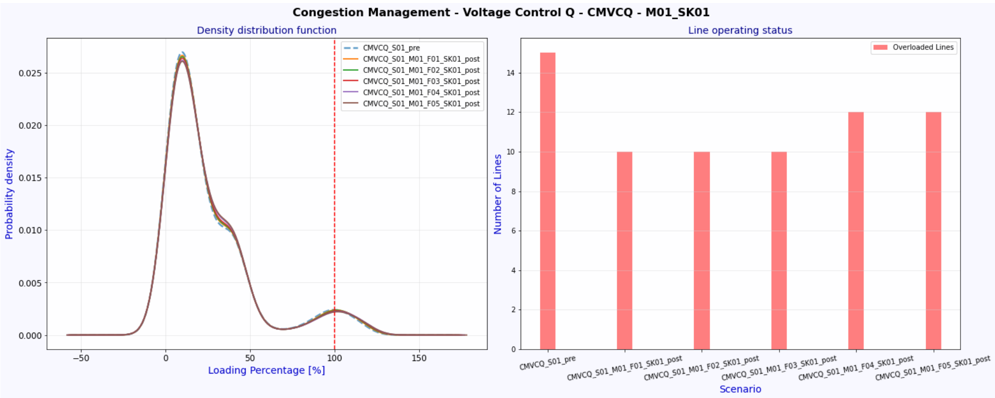
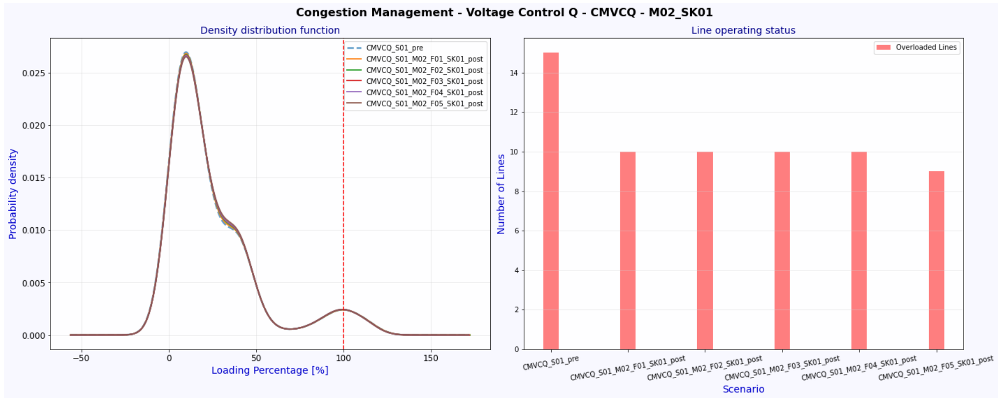


Figure 2.17 Density plots for Loading Percentage [%] of all lines obtained from Congestion Management – Voltage Control with Active Power (a) Scenario M01-K01, (b) Scenario M02-K01, (c) Scenario M01-K02, (d) Scenario M02-K02. Scenario 1, PL-NET1-MV

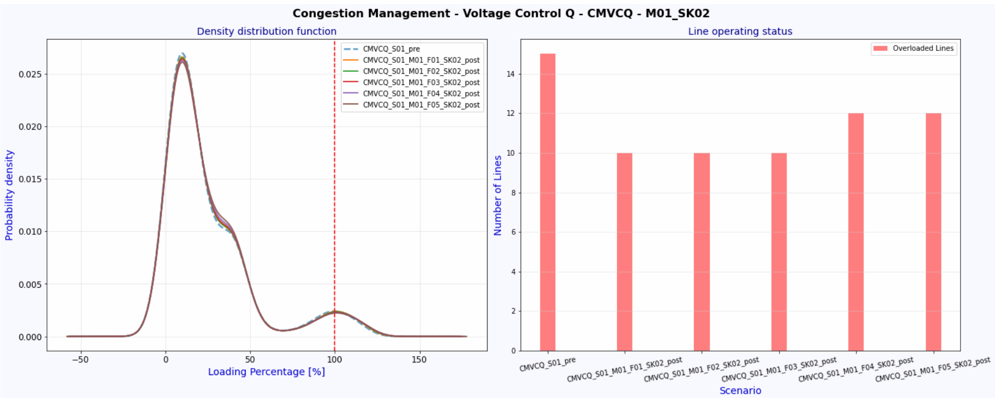
(a)



(c)



(b)



(d)

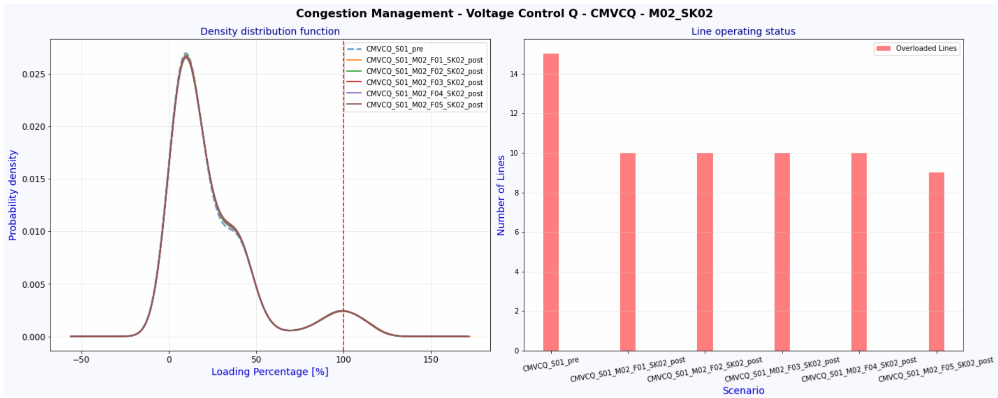


Figure 2.18 Density plots for Loading Percentage [%] of all lines obtained from Congestion Management – Voltage Control with Reactive Power (a) Scenario M01-K01, (b) Scenario M02-K01, (c) Scenario M01-K02, (d) Scenario M02-K02. Scenario 1, PL-NET1-MV

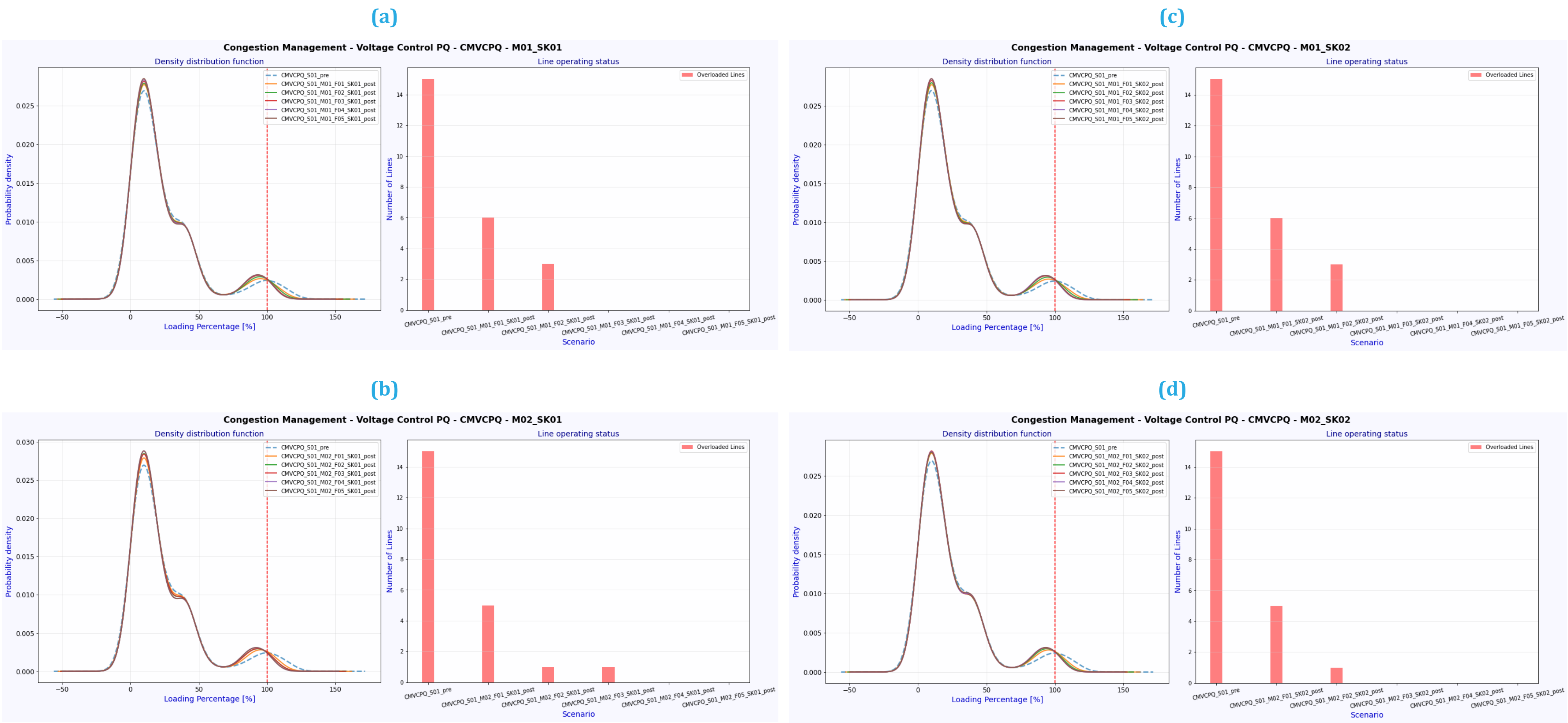


Figure 2.19 Density plots for Loading Percentage [%] of all lines from Congestion Management – Voltage Control with Active and Reactive Power (a) Scenario M01-K01, (b) Scenario M02-K01, (c) Scenario M01-K02, (d) Scenario M02-K02. Scenario 1, PL-NET1-MV

2.2.1.4 Step 4: KPIs calculation

2.2.1.4.1 CM_KPI_4: Avoided Restrictions

This KPI quantifies the number of criticalities, such as line or transformer congestion and bus voltage violations that the market models have resolved. Figure 2.20 and Figure 2.21 display the results of all scenarios for CMVCP and CMVCQ, respectively, considering the sensitivities specified in Table 2.4. Figure 2.22 serves as a comparative analysis, examining how the market dynamics are modified when active and reactive power are used simultaneously in the CMVCPQ market model. The different scenarios are plotted along the horizontal axis, while the vertical axes display, on the left side, the number of restrictions avoided in each component (Nodes, Lines, and Transformers), and on the right side, the Violation Frequency Reduction of the LFM (VFR_LFM) presented as a percentage (red dots).

In the case of the CMVCP market model (Figure 2.20), it can be observed that as the sizes of the FSPs increase (F01 to F05), there is an improvement in the KPI throughout M01 and M02. In M01, it is possible to solve a maximum of approximately 85% of the criticalities, while in M02, up to 100% can be reduced. This outcome is reasonable because the voltage limits used in M02 are slightly more relaxed. Regarding the line congestions, the behaviors across all scenarios display similar trends, as these are given by the maximum thermal capacity of the lines and cannot be relaxed. As mentioned earlier, there are no congestion problems in the transformers.

In the case of the CMVCQ market model (Figure 2.21), a similar behavior as described earlier for M01 can be observed. However, when considering M02, the model encounters some challenges in resolving the existing criticalities, resulting in a reduction of approximately 42% in the best case. This suggests that utilizing reactive power alone may not effectively mitigate criticalities. On the other hand, the CMVCPQ market model presents a significant improvement in the KPI. It successfully resolves up to 100% of the criticalities in similar scenarios with the highest size of the FSPs.

Finally, it is important to note that other market models have been considered to analyze their impact on the grid. Figure 2.23 depicts the results obtained for this KPI when using only Congestion Management (CM) or Voltage Control (VC). It is generally observed that each market model analyzed has a direct impact on the type of criticality avoided, however, it could affect its counterpart.

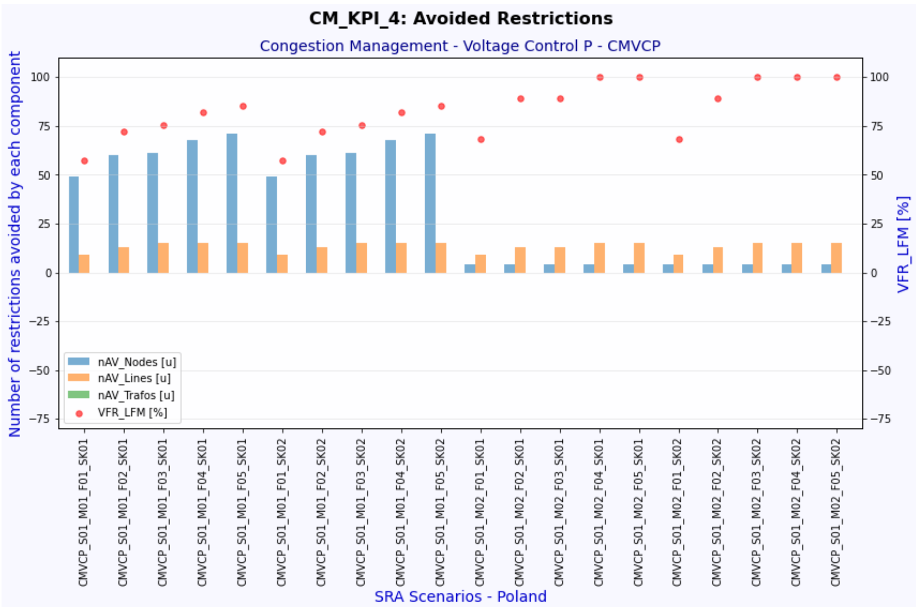


Figure 2.20 KPI CM_SPI_4: Avoided Restrictions, for Congestion Management, Voltage Control using Active Power (CMVCP)

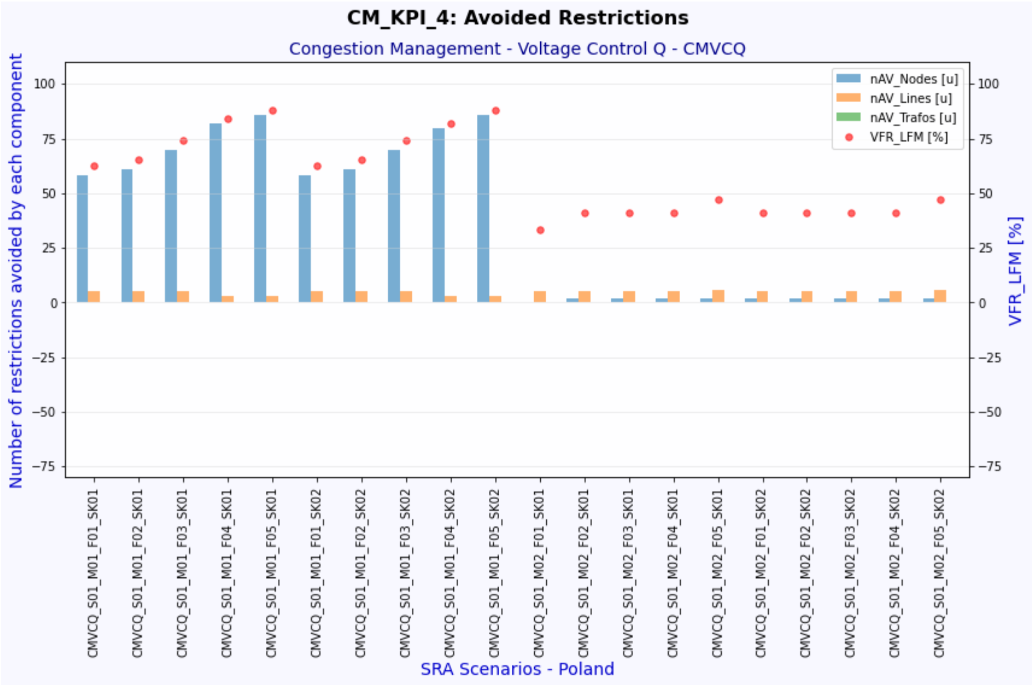


Figure 2.21 KPI CM_SPI_4: Avoided Restrictions, for Congestion Management, Voltage Control using Reactive Power (CMVCQ)

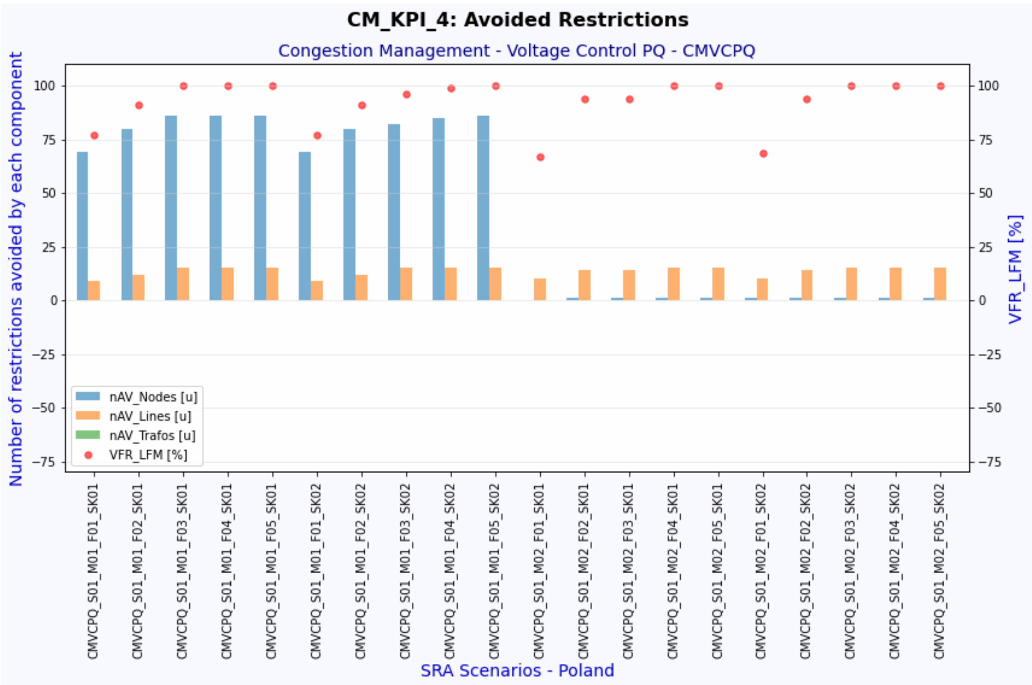
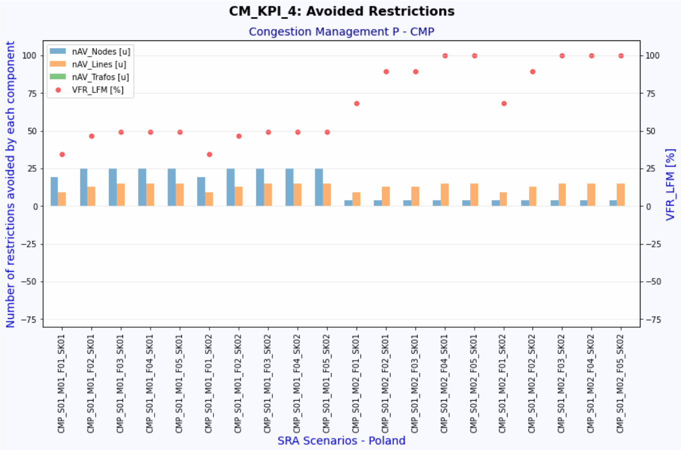
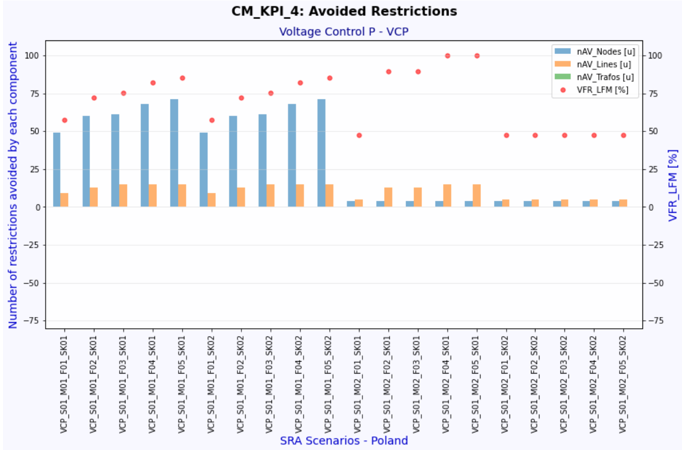


Figure 2.22 KPI CM_SPI_4: Avoided Restrictions, for Congestion Management, Voltage Control using Active Power and Reactive (CMVCPQ)

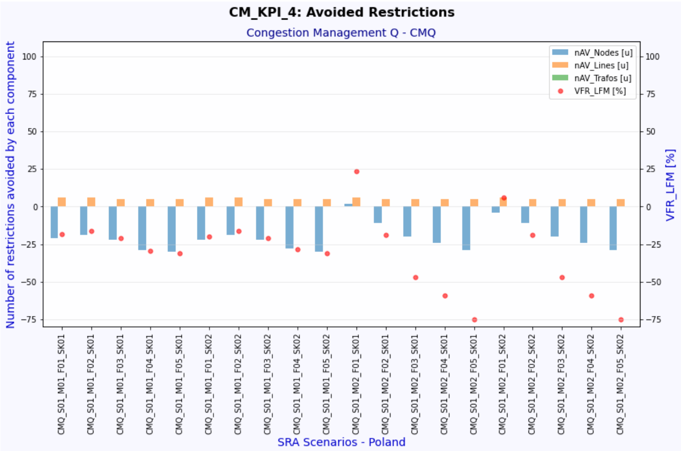
(a1)



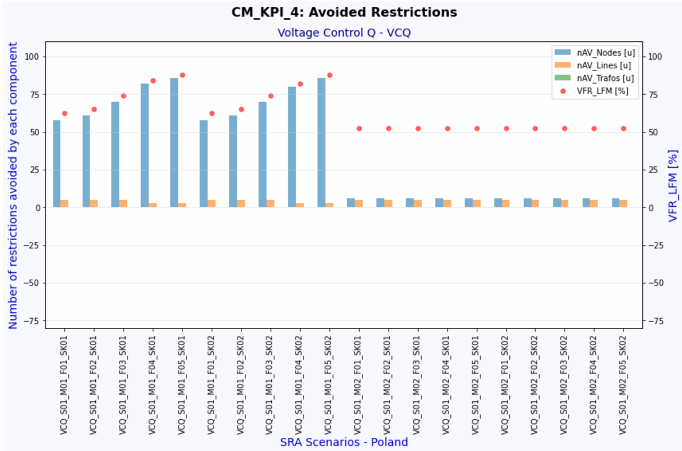
(b1)



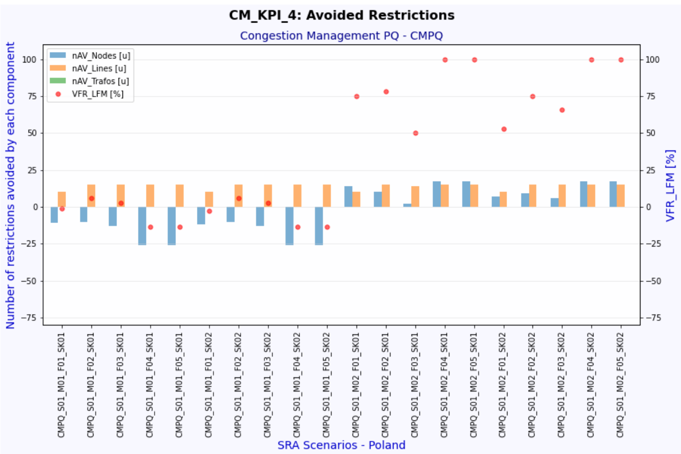
(a2)



(b2)



(a3)



(b3)

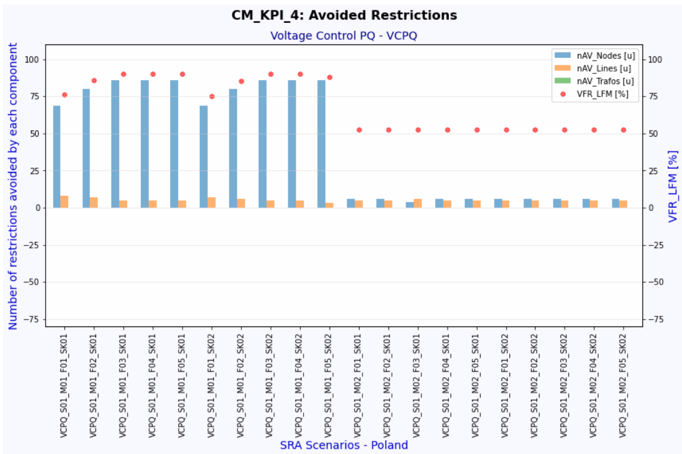


Figure 2.23 CM_KPI_4: Avoided Restrictions:
Congestion Management: a1) Active Power, a2) Reactive Power, a3) Active and Reactive Power.
Voltage Control: b1) Active Power, b2) Reactive Power, b3) Active and Reactive Power

2.2.1.5 Interim conclusions

From the analysis of the Polish demonstrator net 01, it can be concluded that:

- For the quantitative SRA of the Polish demonstrator, two SRA scenarios were tested. Scenario 0 analyzes the PL-NET1-MV network under the conditions of the two representative days, Scenario 0.A (day of maximum load consumption) and Scenario 0.B (day of minimum load consumption), resulting in not congestion events. In addition, due to the large share of DG in this demo site, Scenario 1 examines the congestion events in the network under the same representative day of Scenario 0.A, but the total generation of the network is increased by a factor of 2. Scenario 0.A was selected because this scenario's net generation is higher than Scenario 0.B. The flexibility needs identified in Scenario 1 involve three main criticalities, i) The overloading of two MV lines (L1, L2), ii) Overvoltages problems in buses 5-11 located downstream of the congested lines L1 and L2, and iii) Undervoltage problems in bus 3 located in another MV feeder. With regards to FSPs, most of them (3 WP generators and 1 battery) are located in the same feeder where criticalities i) and ii) occur. There is one FSP (WP plant) located in the feeder where bus overvoltages were identified. A summary of flexibility needs, FSP's characteristics, and the corresponding sensitivity factors were provided in subsection 2.2.1.3.

- The results of SRA Scenario 1 demonstrate that the combined market models for congestion management and voltage control with active power (CMVCP) and reactive power (CMVCQ) can reduce more criticalities as FSPs' flexibility capacity increases. However, these models were unable to entirely eliminate the total amount of criticalities under M01 voltage limits sensitivity even when the models consider the maximum FSPs' flexibility capacity (F05=25%). Both models can resolve a maximum of 85% of the criticalities mentioned earlier. This limitation is because in the CMVCP model the FSPs' active power offers can solve the total number of congestions in L1 and L2, but these bids are not enough to solve the undervoltages in buses located downstream of these lines. By contrast, in the CMVCQ model, the reactive power FSPs offers can solve these undervoltages problems but are not enough to solve the congested lines. However, it is important to note that in the case of CMVCP, if the voltage limits are less restrictive, as observed in scenario M02, the market can successfully resolve 100% of the criticalities. It does not occur when only reactive power is utilized in the CMVCQ market model. These results suggest that relying solely on active or reactive power may not be sufficient to effectively mitigate criticalities in this demo site under the SRA scenario 1 conditions.

- The limitations of CMVCP and CMVCQ models were overcome by the CMVCPQ model, which integrates both active and reactive power products in the LFM market-clearing. For instance, CMVCPQ successfully resolves all criticalities in the network considering 15% of FSPs' flexibility capacity (F03) under M01 SRA scenario 1 conditions. Furthermore, if we compare the LFM objective function (OF) costs reported in Table 2.10 (CMVCP) and Table 2.12 (CMVCPQ) we can see that on average the OF cost of CMVCPQ represents the 25% of OF cost of the CMVCP models. It is important to highlight that this ample cost difference is mainly because the cost of non-supplied flexibility is reduced in the CMVCPQ model.

- Lastly, it is worth mentioning that additional market models have been examined to assess their impact on the network, considering Congestion Management (CM) or Voltage Control (VC) exclusively, with active, reactive, and both products. In our observations, each market model has a higher impact on the related criticality. For example, while CM markets reduce criticalities in the congested feeder, they do not consider the voltage-related problems in other feeders. However, in the VC markets, there are FSPs can solve bus voltage criticalities in all feeders, thus, some of them can also mitigate the congestion lines.

2.3 German demonstrator quantitative SRA

This subsection aims to present and analyze the quantitative SRA results of the German demonstrator, with a specific focus on the two selected demo sites, DE-NET1-LV and DE-NET2-LV. The selection of these demo sites was determined earlier in the chapter (refer to Table 2.1). It is important to note that the content of this subsection follows the four steps proposed in the quantitative SRA methodology, providing details of the input data, SRA scenarios, LFM model, and KPIs results for the DE-NET1-LV in Subsection 2.3.1, and for the DE-NET2-LV in Subsection 2.3.2.

2.3.1 SRA: DE-NET1-LV

2.3.1.1 Step 1: Input data

a) Network characteristics and load and generation profiles

Table 2.13 summarizes the input data for the DE-NET1-LV demo site. For this demo site, an anonymized MV-LV 20/0.4 kV grid was provided by the German demonstrator partners. Although this grid considers MV and LV levels, this SRA is focused on analyzing LV congested elements according to the definition of the demonstrator BUCs. Regarding the network elements, this grid consists of 1885 buses, 1586 lines, 9 secondary substations 20/0.4 kV, 633 load points, and 60 distributed generators (58 PV).

Table 2.13 German demo site characteristics: DE-NET1-LV

Network ID	DE-NET1-LV
Network modeling	Anonymized grid provided by DSO
Grid level	MV-LV grid 20/0.4 kV, the SRA is focused on LV.
Network elements	1885 buses (105 MV buses), 1586 lines, 9 trafos 20/0.4 kV, 633 load points (household, commercial, heat storage, heat pumps, industrial, street lighting), 60 DGs (58 PV, 2 CHP).
Load and Generation profiles	Yearly profiles (8760 hours) Load profiles data provided by DSO (household, commercial, and street lighting), year 2014. Heat storage, heat pumps, industrial load profiles, PV, and CHP profiles based on literature information.
FSPs	Selection of FSPs based on SRA scenarios: 50 FSPs (load and generation)

For this demo site, load and generation profiles were defined on an hourly basis for a full year, i.e., for 8760 operation points. It is important to highlight that the German demonstrator partners supplied annual load profiles, including typical profiles for household, commercial, and street lighting loads. Regarding electric heat storage loads, annual temperature-dependent profiles were built based on the registered temperature of the demo site obtained from [20] and normalized profiles for this type of load described in [21]. In the case of PV (photovoltaic), production profiles were built based on normalized profiles from the PVGIS database [20] and the location and installed capacity of PV plants.

b) FSPs characteristics

Table 2.14 describes the FSPs considered in the DE-NET1-LV demo site. The selection of FSPs' location and quantity was defined according to the SRA Scenario 1, further described in subsection 2.3.1.2. In this scenario, congestion events are analyzed along the LV feeder of transformer T0 (20/0.4 kV), so all load and generator elements connected to this feeder were chosen as FSPs. The flexibility costs information for active power was obtained from the Picloflex platform [15], and the reactive power flexibility cost was considered 5% of the active power bids cost assuming that the reactive power costs are due to the internal active power losses caused for the keeping the established reactive power set-point. [16]–[18]. Moreover, it should be noted that most of the FSPs offer upward and downward flexibility (active and reactive) except PV generators that don't provide active upward flexibility. For the SRA, we consider that each FSP has an available flexibility of 5% of its maximum capacity (base case). Based on the capability analysis of DERs operating curves, the value of 5% is also considered for reactive power bids [16].

Table 2.14 FSPs Characteristics, German demonstrator DE-NET1-LV

FSP ID	Bus ID	FSP type	Nominal capacity [MVA]	Active power upward capacity [%]	Active power downward capacity [%]	Active power upward cost [EU/MWh]	Active power downward cost [EU/MWh]	React. power upward capacity [%]	React. power downward capacity [%]	React. power upward cost [EU/MWh]	React. power downward cost [EU/MWh]
fsp1	63	load	0.00318	5.00%	5.00%	39.99	39.85	5.00%	5.00%	2.00	1.99
fsp2	63	gen	0.0152	0.00%		40.21	39.61			2.01	1.98
fsp3	78	load	0.00342	5.00%		39.83	39.64			1.99	1.98
fsp4	78	gen	0.00192	0.00%		39.85	40.09			1.99	2.00
fsp5	210	load	0.00238	5.00%		39.99	39.52			2.00	1.98
fsp6	210	gen	0.00835	0.00%		39.66	40.13			1.98	2.01
fsp7	644	load	0.00559	5.00%		39.63	39.98			1.98	2.00
fsp8	644	gen	0.00728	0.00%		39.88	40.05			1.99	2.00
fsp9	654	load	0.00363	5.00%		39.49	40.08			1.97	2.00
fsp10	654	gen	0.0065	0.00%		39.78	39.77			1.99	1.99
fsp11	657	load	0.00309	5.00%		39.56	39.61			1.98	1.98
fsp12	657	gen	0.02422	0.00%		39.4	39.72			1.97	1.99
fsp13	727	load	0.00318	5.00%		40.19	40.03			2.01	2.00
fsp14	727	gen	0.00343	0.00%		39.74	39.76			1.99	1.99
fsp15	1074	load	0.01089	5.00%		40.16	39.86			2.01	1.99
fsp16	1074	gen	0.03167	0.00%		39.69	39.85			1.98	1.99
fsp17	1099	load	0.00463	5.00%		39.61	39.39			1.98	1.97
fsp18	1099	gen	0.0062	5.00%		39.46	39.65			1.97	1.98
fsp19	1113	load	0.00318	5.00%		39.87	40.25			1.99	2.01
fsp20	1113	gen	0.0025	0.00%		40.04	39.64			2.00	1.98
fsp21	1161	load	0.00238	5.00%		39.62	39.83			1.98	1.99
fsp22	1161	gen	0.0062	5.00%		39.55	39.66			1.98	1.98
fsp23	1184	load	0.00559	5.00%		39.75	39.74			1.99	1.99
fsp24	1184	gen	0.00375	0.00%		39.61	39.56			1.98	1.98
fsp25	1185	load	0.00318	5.00%		39.96	39.75			2.00	1.99
fsp26	1185	gen	0.009	0.00%		39.97	39.74			2.00	1.99
fsp27	1290	load	0.00412	5.00%		39.33	39.57			1.97	1.98
fsp28	1290	gen	0.008	0.00%		40.13	39.22			2.01	1.96
fsp29	1303	load	0.00363	5.00%		40.02	39.96			2.00	2.00
fsp30	1303	gen	0.003	0.00%		39.6	40.19			1.98	2.01
fsp31	1359	load	0.00412	5.00%		39.57	40.06			1.98	2.00
fsp32	1359	gen	0.00235	0.00%		39.25	40.09			1.96	2.00
fsp33	1461	load	0.00469	5.00%		39.89	39.55			1.99	1.98
fsp34	1461	gen	0.00547	0.00%		40.08	40.14			2.00	2.01
fsp35	1546	load	0.03633	5.00%		39.9	39.32			2.00	1.97
fsp36	1546	gen	0.00315	0.00%		39.95	40.15			2.00	2.01
fsp37	1557	load	0.00363	5.00%		39.82	40.29			1.99	2.01
fsp38	1557	gen	0.0046	0.00%		40.21	39.83			2.01	1.99
fsp39	1561	load	0.00363	5.00%		40.03	40.06			2.00	2.00
fsp40	1561	gen	0.00527	0.00%		39.41	39.82			1.97	1.99
fsp41	1570	gen	0.00717	0.00%		39.58	39.66			1.98	1.98
fsp42	1690	load	0.00412	5.00%		39.66	40.41			1.98	2.02
fsp43	1690	gen	0.004	0.00%		39.86	40.41			1.99	2.02
fsp44	1703	load	0.00342	5.00%		39.73	40.06			1.99	2.00
fsp45	1703	gen	0.016	0.00%		39.79	40.14			1.99	2.01
fsp46	1733	gen	0.008	0.00%		39.45	39.96			1.97	2.00
fsp47	1748	load	0.00363	5.00%		39.76	39.78			1.99	1.99
fsp48	1748	gen	0.0046	0.00%		39.72	40.17			1.99	2.01
fsp49	1841	load	0.0043	5.00%		39.37	39.76			1.97	1.99
fsp50	1841	gen	0.0046	0.00%		39.76	39.81			1.99	1.99

2.3.1.2 Step 2: SRA scenarios

Different scenarios are tested for the quantitative SRA of the DE-NET1-LV demo site according to Table 2.15. This table also summarizes the SRA parameters and the KPIs to be calculated for each scenario. Two scenarios are defined. First, we analyzed the DE-NET1-LV network considering the load and generation annual profiles described in the previous subsection (Scenario 0), resulting in no congested elements. Second, Scenario 1 examines the congestion events in the network under the conditions of Scenario 0, but the consumption of load elements connected to the LV feeder of transformer T0 (20/0.4 kV) was increased by 25%. The focus is on this feeder as its elements were identified as being closest to congested during the Scenario 0 assessment. The quantitative SRA methodology is applied for each of these scenarios, and the results are further analyzed in the following subsections.

Table 2.15 SRA scenarios for the German demonstrator DE-NET1-LV

Scenario ID	Description	SRA parameters	KPIs
Scenario 0	Initial yearly profiles	No congested elements	
Scenario 1	Increasing load in T0 (20/0.4 kV) feeder by 25%	Load scaling up, FSPs bid size, Bus voltage limits.	EU_KPI_1: Increased RES and DER hosting capacity EU_KPI_2: Increase of energy storage solutions penetration CM_KPI_4: Avoided restrictions

2.3.1.3 Step 3: LFM model

a) SRA Scenario 0

The SRA methodology described in Subchapter 2.1 is applied for Scenario 0 of DE-NET1-LV. Therefore, this section describes the results of the required steps considered for this methodology:

- **Flexibility needs calculation (Step 3.1):** The first step is to perform a power flow analysis for 8760 hours (market horizon) to identify possible constraints in the grid. This analysis considers network data, and load and generation initial profiles described in section 2.2.1.1. Figure 2.24, Figure 2.25, and Figure 2.26 present the results for the Scenario 0 conditions. These results show that congestion problems (lines and transformers overloading events) do not occur under this scenario. By contrast, as shown in Figure 2.26, the voltage magnitude of some buses is less than 0.95 p.u in January and December.

  It is important to note that the resulting flexibility needs are focused only on voltage control, which is not in line with the objective of the BUCs in the German demonstrator, to test a LFM for both congestion management and voltage control services. Therefore, it becomes necessary to define a new scenario that aligns with this objective, which is analyzed in the following subsection.

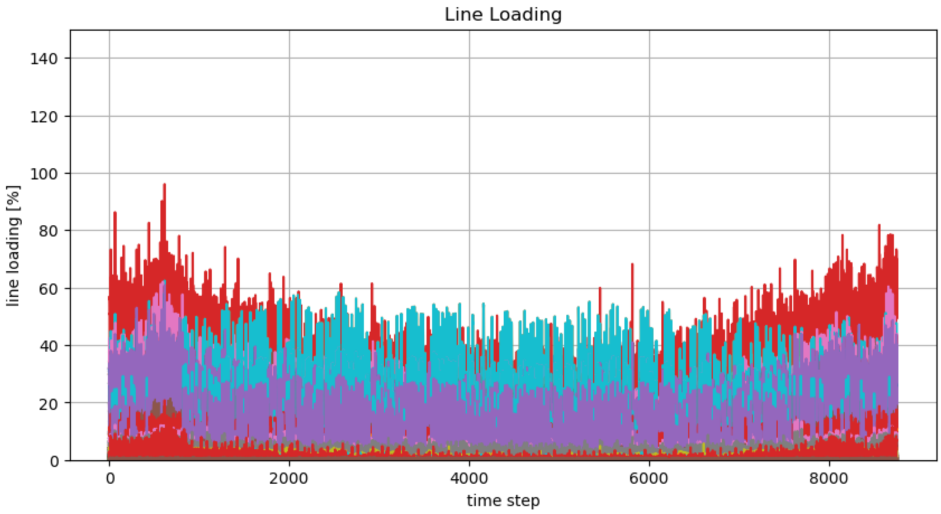


Figure 2.24 Lines loading [%] for the Scenario 0, DE-NET1-LV

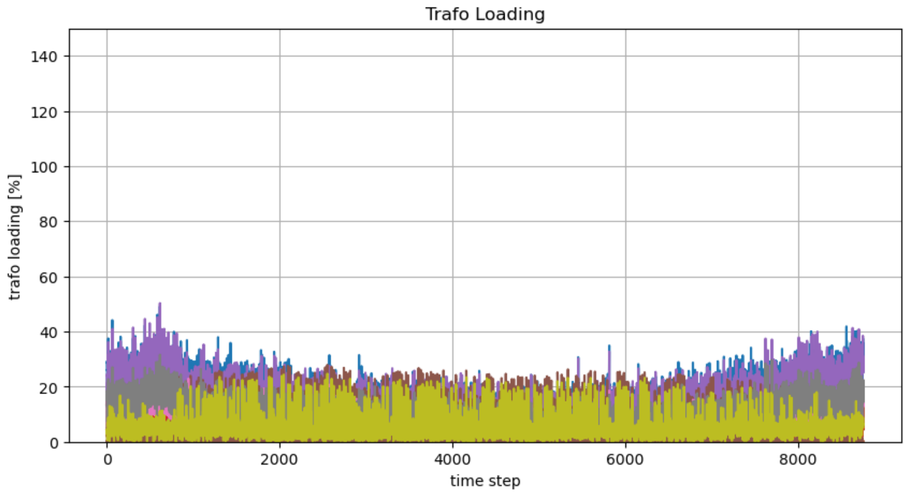


Figure 2.25 Transformers loading [%] for the Scenario 0, DE-NET1-LV

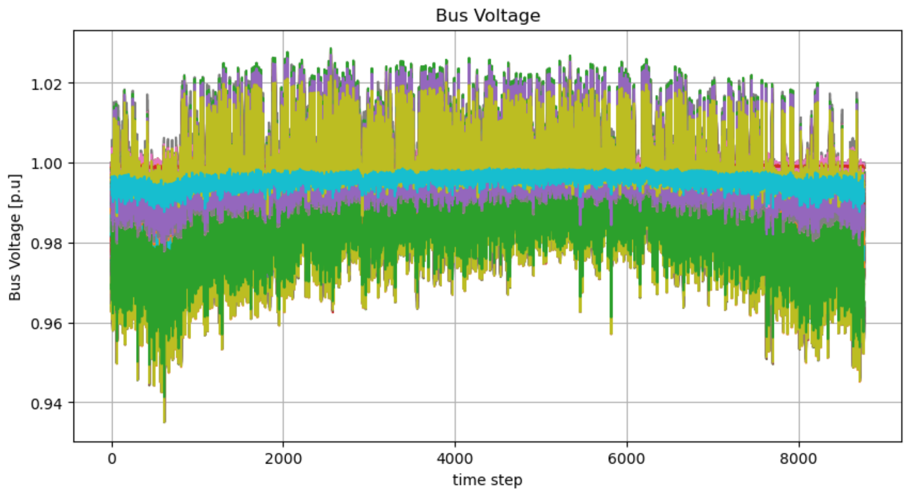


Figure 2.26 Buses Voltage [p.u.] for the Scenario 0, DE-NET1-LV

b) SRA Scenario 1

This section presents the results obtained by applying the quantitative SRA methodology for Scenario 1 of DE-NET1-LV, which was defined in Table 2.15. This scenario examines the congestion events in the network under the conditions of Scenario 0, but the consumption of load elements connected to the LV feeder of transformer T0 (20/0.4 kV) was increased by 25%. The results are described below for each step of the SRA methodology.

- **Flexibility needs calculation (Step 3.1):** Considering the new load profiles, a power flow analysis is run for 8760 hours to identify potential constraints. Figure 2.27, Figure 2.28, and Figure 2.29 present results for lines loading, transformers loading, and bus voltage magnitude, respectively. From Figure 2.27, we identified that line 23 is congested under this scenario. In addition, from Figure 2.29, we can observe that some buses have undervoltage values (below 0.95 p.u.). In this scenario, there are no congestion problems in the transformers, see Figure 2.29.

  Considering power flow results, the corresponding flexibility needs are computed. Table 2.16 summarizes scenario 1 flexibility needs and network issues associated with congestion management and voltage control, resulting in 11 congestion problems and 1113 voltage violations. These values are determined by considering the number of congested elements multiplied by the hours when these problems occur.

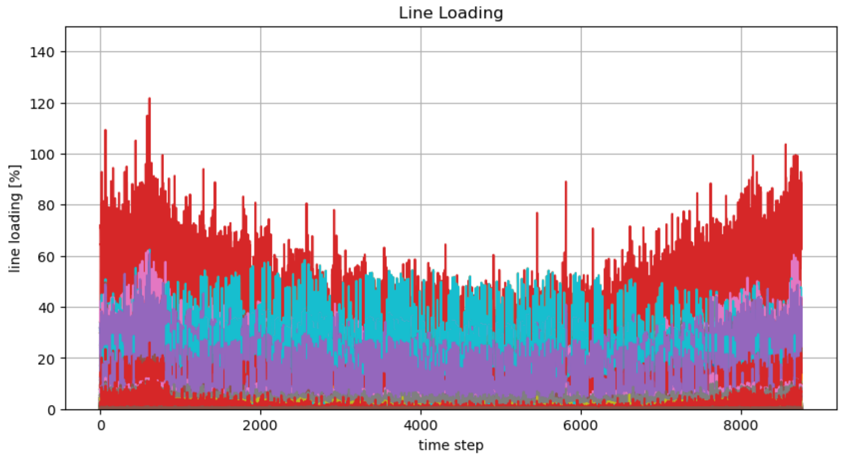


Figure 2.27 Lines loading [%] for the Scenario 1, DE-NET1-LV

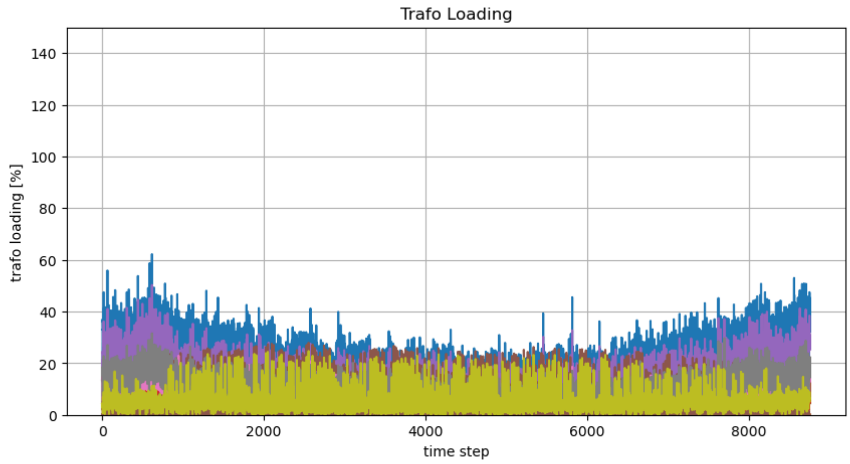


Figure 2.28 Transformer loading [%] for the Scenario 1, DE-NET1-LV

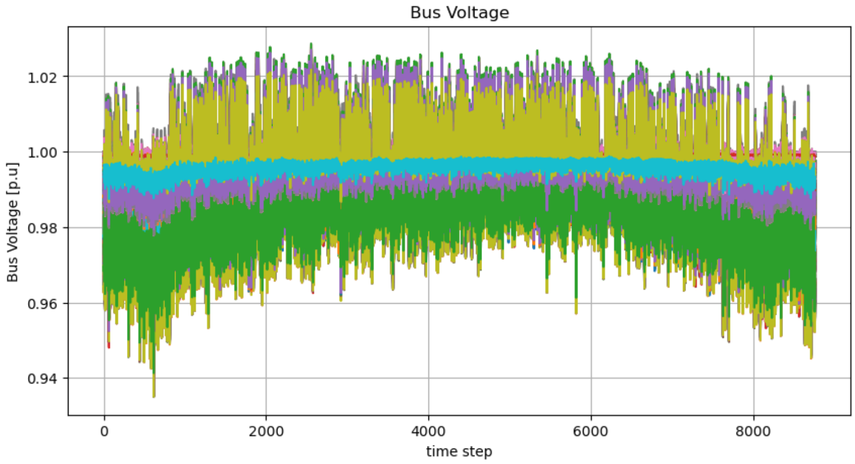


Figure 2.29 Bus Voltage [p.u.] for the Scenario 1, DE-NET1-LV

Table 2.16 Summary of Flexibility Needs for DE-NET1-LV

Congestion management and voltage control flexibility needs	Value
Congested lines and/or transformers	Line # 23
Total congestion problems (congested elements by hours)	11
Overvoltage problems (bus with overvoltage by hours)	0
Undervoltage problems (bus with undervoltage by hours)	1113

- **Sensitivity factors calculation (Step 3.2):** In this step, sensitivity factors are computed for each FSP participating in the local market relative to the flexibility needs obtained in the previous step. As stated in Section 2.1, sensitivity factors for congestion management describe how the apparent power of a congested line or transformer could be impacted by variations in the active (dS/dP) or reactive (dS/dQ) power provided by FSPs. For voltage control, sensitivity factors indicate how the voltage at a specific node could be impacted by variations in active (dV/dP) or reactive (dV/dQ) power provided by the FSP. Table 2.17 and Table 2.18 summarize the resulting sensitivity factors for both services. It should be emphasized that the sensitivity factors have been computed for each hour of study (hours with congestion events in lines, transformers, or buses). For simplicity, the values shown in both tables correspond to the mean ± standard deviation of all hourly values obtained by each type of FSP.

  Regarding congestion management, Table 2.17 indicates that changes in active power (P) and reactive power (Q) in all FSPs impact the apparent power (S) of line L23 with factors very close to unity in the case of P (column 1), and with smaller factors in the case of Q (column 2). The negative sign of the sensitivity factors implies an inverse relationship, which means that an increase in P or Q in FSP results in a decrease in the S value of the congested element.

  With regards to voltage control, Table 2.18 provides a summary of computed sensitivity factors for the bus with the lowest value – premarket p.u., as an example. It can be observed that both active and reactive power injections from FSP 46 impact node 1733, while the rest of the FSPs do not influence this node.

Table 2.17 Sensitivity factors for congestion management, DE-NET1-LV (8)

FSP ID			FSP type	Sensitivity factors L23 dS/dP	Sensitivity factors L23 dS/dQ
fsp1	fsp3	fsp5	Load	-0.995 ± 3.70e-10	-0.329 ± 4.93e-10
fsp7	fsp9	fsp11			
fsp13	fsp15	fsp17			
fsp19	fsp21	fsp23			
fsp25	fsp27	fsp29			
fsp31	fsp33	fsp35			
fsp37	fsp39	fsp42			
fsp44	fsp47	fsp49			
fsp2	fsp4	fsp6	Generation	-0.994 ± 3.79e-10	-0.329 ± 4.75e-10
fsp8	fsp10	fsp12			
fsp14	fsp16	fsp18			
fsp20	fsp22	fsp24			
fsp26	fsp28	fsp30			
fsp32	fsp34	fsp36			
fsp38	fsp40	fsp41			
fsp43	fsp45	fsp46			
fsp48	fsp50				

Table 2.18 Sensitivity factors for voltage control, DE-NET1-LV (9)

FSP ID			FSP type	Sensitivity factors Bus 1733 (Lowest Value - premarket) dV/dP	Sensitivity factors Bus 1733 (Lowest Value - premarket) dV/dQ
fsp1	fsp3	fsp5	Load	0	0
fsp7	fsp9	fsp11			
fsp13	fsp15	fsp17			
fsp19	fsp21	fsp23			
fsp25	fsp27	fsp29			
fsp31	fsp33	fsp35			
fsp37	fsp39	fsp42			
fsp44	fsp47	fsp49			
fsp2	fsp4	fsp6	Generation	0	0
fsp8	fsp10	fsp12			
fsp14	fsp16	fsp18			
fsp20	fsp22	fsp24			
fsp26	fsp28	fsp30			
fsp32	fsp34	fsp36			
fsp38	fsp40	fsp41			
fsp43	fsp45	fsp48			
	fsp50				
	fsp46			0.191	0.192

- **FSP's bid generation (Step 3.3):** This step computes the flexibility limit that each FSP can provide, both downward and upward, for active and reactive power, based on its

[8] Sensitivity factors have been computed for each hour of study. For simplicity, the reported values correspond to the mean ± standard deviation of the all hourly values obtained.

[9] Sensitivity factors have been computed for each hour of study. For simplicity, the reported values correspond to the mean ± standard deviation of the all hourly values obtained.

characteristics provided in Table 2.4 and the network operational conditions established in Scenario 1.

- **Local flexibility market-clearing (Step 3.4) and post-evaluation (Step 3.5):** In step 3.4, a local flexibility market-clearing is carried out to solve the criticalities identified in step 3.1 using the most efficient flexibility bids from FSPs (step 3.3) at minimum cost. The LFM clearing considers the sensitivities factors computed in step 3.2 as a representation of the network constraints. To evaluate the SRA performance of scenario 1, sensitivities are applied to the same three key parameters considered in the Polish demonstrator. Furthermore, it should be emphasized that a cost of 12410 (EUR/MWh) is considered for the $VOLL$ parameter in the German demonstrator according to the report in [19].

Table 2.19 Sensitivities to the SRA parameters for Scalability, Scenario 1, DE-NET1-LV

Parameter	Parameter description	Sensitivity Range
M01 M02	Limits of maximum and minimum permissible voltage levels for buses	$M0x = [v_{min}, v_{max}]$ $M01 = [0.95, 1.05]$ $M02 = [0.93, 1.07]$
F01 F03 F05	Increase in available flexibility from FSPs	*F0x* = [5%, 15%, 25%]
SK01	Increase in storage capacity.	*SK0x* = [Nominal Capacity]

According to Table 2.1, the main BUC LFM models required for the German Network involve Congestion Management and Voltage Control utilizing active power (CMVCP) and reactive power (CMVCQ). Table 2.23 and Table 2.21 summarize the results obtained after the market clearing for each scenario that has been evaluated considering the sensitivities from Table 2.19. In both tables, the cost of the Objective Function equals the sum of the costs of the total active and reactive power FSP's bids cleared in the market plus the cost of the auxiliary variables Alpha and Beta, which implies that the model has been satisfactorily solved. Alpha represents the cost of the flexibility not supplied by the Voltage Control component, while Beta corresponds to the cost of the flexibility not supplied by the Congestion Management component[10]. As the capacities of the FSPs increase (from F01 to F05), the associated costs of Alpha and Beta decrease. Given the high costs attributed to these factors, their reduction aligns with the model's objective to minimize total costs. Furthermore, it can be noted that under conditions with lower voltage boundary constraints (specifically M02 in comparison to M01), the cost of Alpha becomes zero.

It should be noted that in the case of CMVCP, there are no costs associated with reactive power. Similarly, in the case of CMVCQ, the active power cost column is empty. This logical result arises from the fact that these types of offers compete exclusively in their respective markets. Table 2.22 presents additionally the results obtained by considering a LFM models for Congestion Management and Voltage Control, where both active and reactive power are simultaneously taken into account. It can be seen that this model achieves a greater reduction in total costs compared to the two previous cases, potentially due to a lower unsupplied flexibility. The observed trend of cost

[10] A comprehensive description of Alpha and Beta can be found in the LFM formulation of Annex II.

reduction is consistent with the previous cases and there are costs associated with both active and reactive power that they have been matched in the market.

Table 2.20 Summary of costs resulting from the market clearing for congestion management and voltage control with active power, Scenario 1, DE-NET1- LV

Scenario	Objective Value [EUR]	Beta Cost [EUR]	Alpha Cost [EUR]	Total Active Power [MW]	Active Power Cost [EUR]	Total Reactive Power [MVAR]	Reactive Power Cost [EUR]
CMVCP_S01_M01_F01_SK01	226.833,92	4.064,32	222.768,61	0,02	0,98	-	-
CMVCP_S01_M01_F03_SK01	226.091,06	3.401,72	222.686,36	0,07	2,94	-	-
CMVCP_S01_M01_F05_SK01	225.362,97	2.752,69	222.605,36	0,12	4,86	-	-
CMVCP_S01_M02_F01_SK01	4.065,31	4.064,32	-	0,02	0,98	-	-
CMVCP_S01_M02_F03_SK01	3.404,70	3.401,72	-	0,07	2,94	-	-
CMVCP_S01_M02_F05_SK01	2.757,61	2.752,69	-	0,12	4,86	-	-

Table 2.21 Summary of costs resulting from the market clearing for congestion Management and voltage control with reactive power, Scenario 1, DE-NET1- LV

Scenario	Objective Value [EUR]	Beta Cost [EUR]	Alpha Cost [EUR]	Total Active Power [MW]	Active Power Cost [EUR]	Total Reactive Power [MVAR]	Reactive Power Cost [EUR]
CMVCQ_S01_M01_F01_SK01	227.013,32	4.231,80	222.781,45	-	-	0,04	0,08
CMVCQ_S01_M01_F03_SK01	226.627,90	3.910,63	222.717,04	-	-	0,12	0,24
CMVCQ_S01_M01_F05_SK01	226.410,37	3.724,31	222.685,74	-	-	0,16	0,33
CMVCQ_S01_M02_F01_SK01	4.231,88	4.231,80	-	-	-	0,04	0,08
CMVCQ_S01_M02_F03_SK01	3.910,87	3.910,63	-	-	-	0,12	0,24
CMVCQ_S01_M02_F05_SK01	3.724,63	3.724,31	-	-	-	0,16	0,33

Table 2.22 Summary of resulting costs from the market clearing for congestion management and voltage control with active and reactive power, Scenario 1, DE-NET1- LV

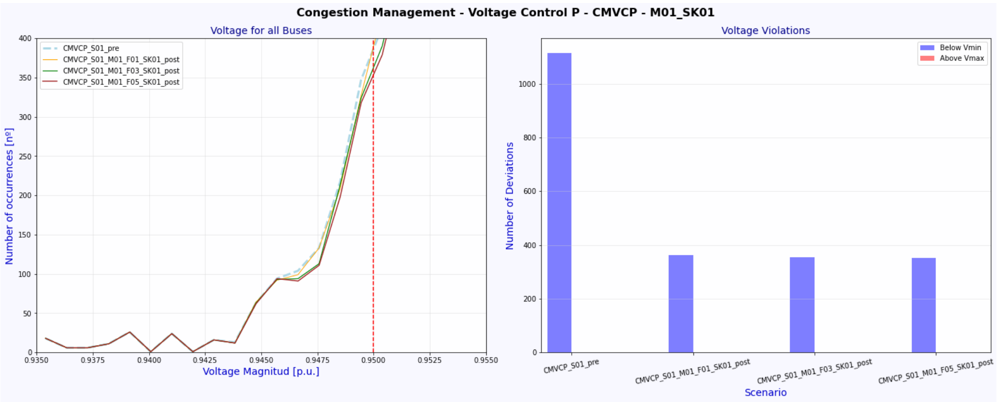
Scenario	Objective Value [EUR]	Beta Cost [EUR]	Alpha Cost [EUR]	Total Active Power [MW]	Active Power Cost [EUR]	Total Reactive Power [MVAR]	Reactive Power Cost [EUR]
CMVCPQ_S01_M01_F01_SK01	226.638,62	3.900,49	222.737,05	0,02	0,98	0,05	0,09
CMVCPQ_S01_M01_F03_SK01	225.562,69	2.964,16	222.595,45	0,07	2,80	0,14	0,27
CMVCPQ_S01_M01_F05_SK01	224.751,87	2.263,80	222.483,25	0,11	4,37	0,22	0,44
CMVCPQ_S01_M02_F01_SK01	3.901,57	3.900,49	-	0,02	0,98	0,05	0,09
CMVCPQ_S01_M02_F03_SK01	2.967,23	2.964,16	-	0,07	2,80	0,14	0,27
CMVCPQ_S01_M02_F05_SK01	2.268,51	2.263,80	-	0,11	4,33	0,19	0,38

As technical results, Figure 2.30, Figure 2.31, and Figure 2.32 show the number of occurrence plots of all bus voltages [p.u.], before (pre) and after (post) the market, for CMCVP, CMCVQ, and CMCVPQ, across each considered scenario. Moreover, the bar plots display the changes in voltage violations for each scenario. Similarly, Figure 2.33, Figure 2.34, and Figure 2.35 present number of occurrence plots illustrating the load percentage of lines, while the corresponding bar graphs specifically highlight the lines experiencing congestion problems.

From the voltage plots, it can be seen that as the size of the FSPs increase (from F01 to F05), bus voltages tend to converge within the voltage limits compared to the pre-market conditions. The bar plots show that in M01 cases, the undervoltage problems that were present before the market significantly decrease. Comparing the impacts of CMVCP, CMVCQ, and CMVCPQ model markets, for M01, it can be observed that the latter achieves a remarkable reduction in undervoltage problems as FSPs size increase. In the case of scenario M02, there are not important issues to be considered, but there has been an improvement in bus voltages by shifting to the centre of the plots.

Similar behavior can be observed in the graphs depicting the lines, where the number of occurrence plot moves closer to the maximum thermal limit as the size of the FSPs increase. Notably, the CMVCPQ market model consistently achieves better results compared to CMVCP and CMVCQ in terms of congestion management. Interestingly, when considering only the use of reactive power for congestion management, increasing the capacity of FSPs to provide reactive power does not seem to effectively solve congestion problems. This suggests that the utilization of reactive power alone may not be sufficient to mitigate congestion effectively.

(a)



(b)

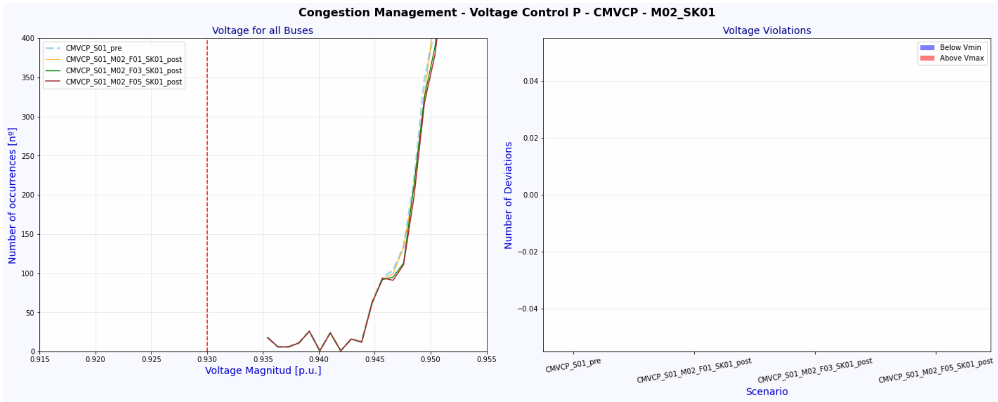
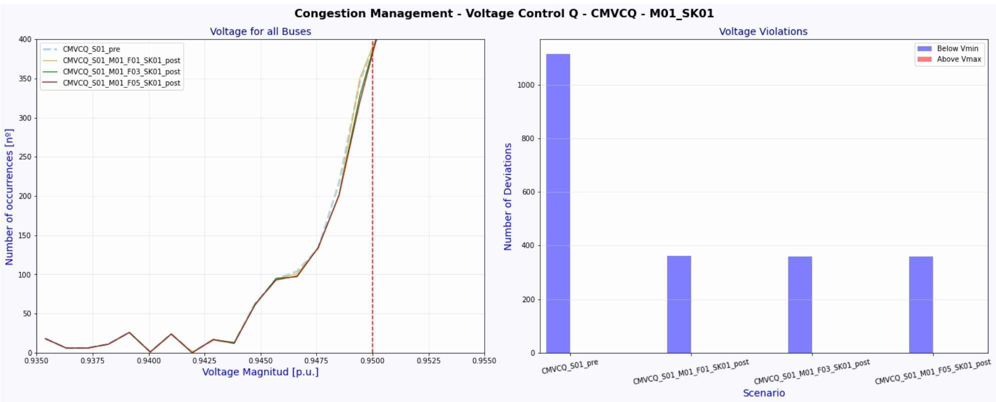


Figure 2.30 Deviation plots for Voltage Magnitude [p.u.] obtained from Congestion Management – Voltage Control with Active Power (a) Scenario M01-K01, (b) Scenario M02-K01. Scenario 1, DE-NET1-LV.

(a)



(b)

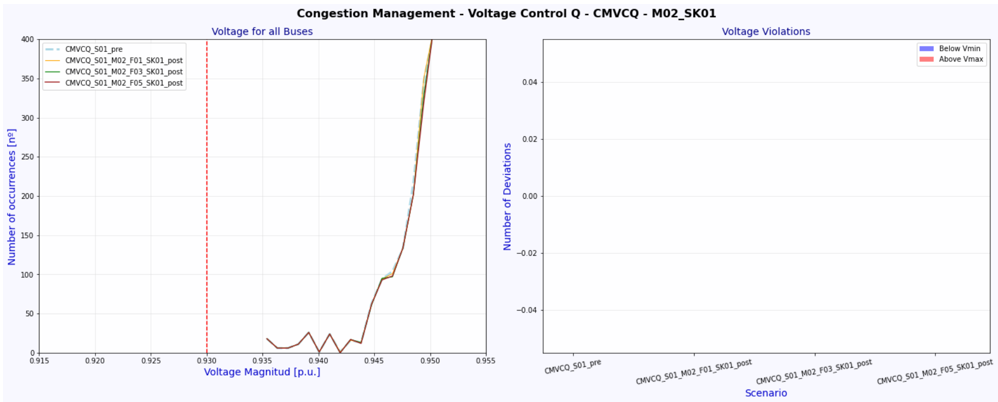


Figure 2.31 Deviation plots for Voltage Magnitude [p.u.] obtained from Congestion Management – Voltage Control with Reactive Power (a) Scenario M01-K01, (b) Scenario M02-K01. Scenario 1, DE-NET1-LV.

(a) (b)

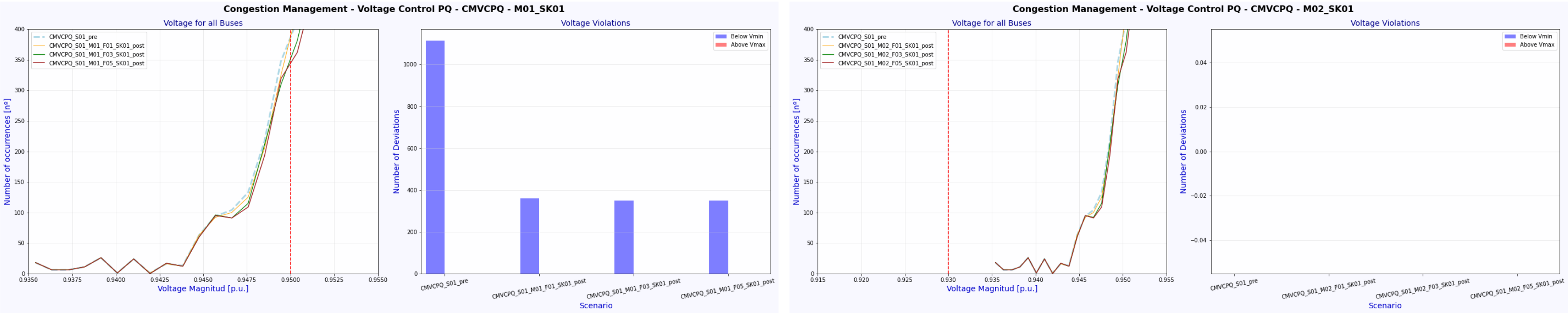


Figure 2.32 Deviation plots for Voltage Magnitude [p.u.] obtained from Congestion Management – Voltage Control with Active and Reactive Power (a) Scenario M01-K01, (b) Scenario M02-K01. Scenario 1, DE-NET1-LV.

(a) (b)

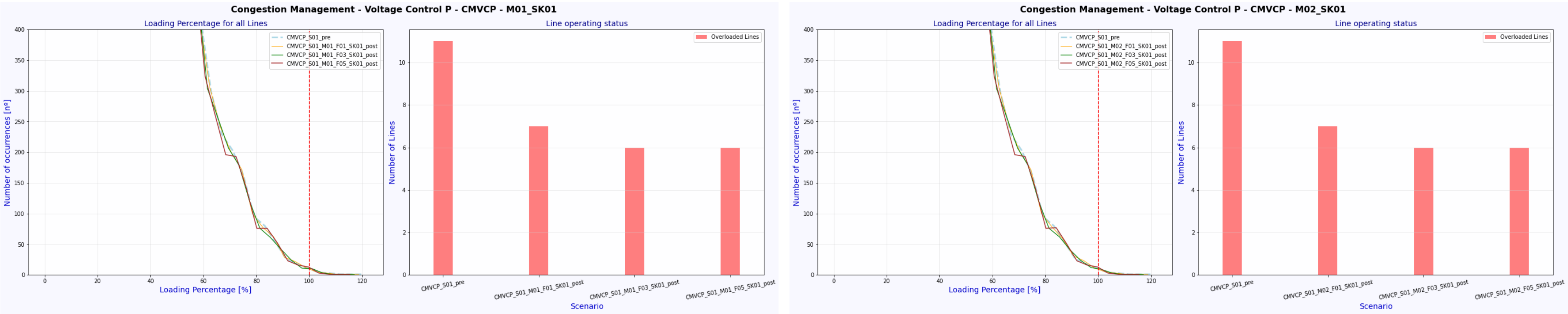


Figure 2.33 Deviation plots for Loading Percentage [%] of all lines obtained from Congestion Management – Voltage Control with Active Power (a) Scenario M01-K01, (b) Scenario M02-K01. Scenario 1, DE-NET1-LV.

(a) (b)

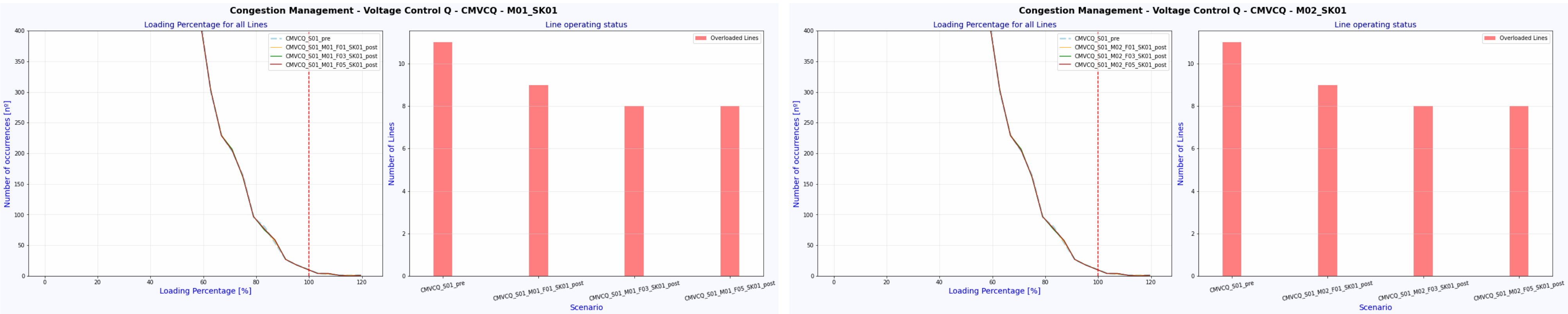


Figure 2.34 Deviation plots for Loading Percentage [%] of all lines obtained from Congestion Management – Voltage Control with Reactive Power (a) Scenario M01-K01, (b) Scenario M02-K01. Scenario 1, DE-NET1-LV.

(a) (b)

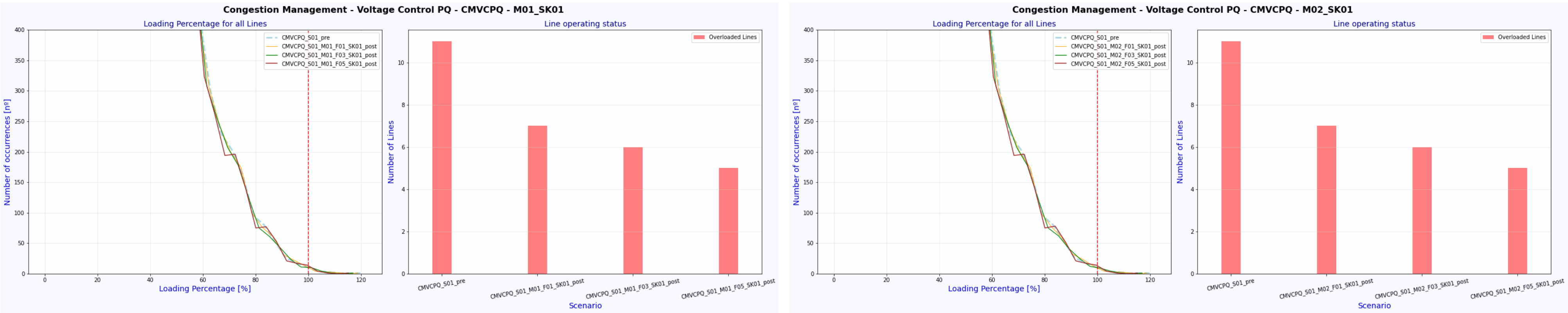


Figure 2.35 Deviation plots for Loading Percentage [%] of all lines obtained from Congestion Management – Voltage Control with Active and Reactive Power (a) Scenario M01-K01, (b) Scenario M02-K01. Scenario 1, DE-NET1-LV.

2.3.1.4 Step 4: KPIs calculation

2.3.1.4.1 CM_KPI_4: Avoided Restrictions

This KPI quantifies the number of criticalities, such as line or transformer congestion and bus voltage violations that the market models have resolved. Figure 2.36 and Figure 2.37 display the results of all scenarios for CMVCP and CMVCQ, respectively, considering the sensitivities specified in Table 2.14. Figure 2.38 serves as a comparative analysis, examining how the market dynamics are modified when active and reactive power are used simultaneously in the CMVCPQ market model. The different scenarios are plotted along the horizontal axis, while the vertical axes display, on the left side, the number of restrictions avoided in each component (Nodes, Lines, and Transformers), and on the right side, the Violation Frequency Reduction of the LFM (VFR_LFM) presented as a percentage (red dots).

Finally, it is important to note that other market models have been considered to analyze their impact on the grid. Figure 2.39 depicts the results obtained for this KPI when using only Congestion Management (CM) or Voltage Control (VC).

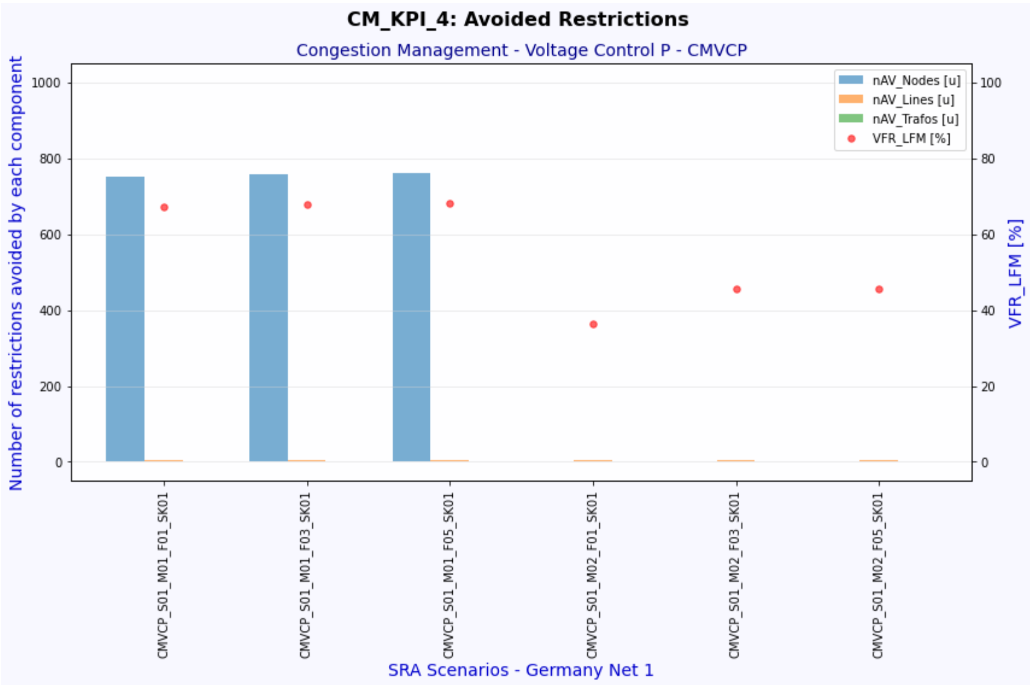


Figure 2.36 KPI CM_SPI_4: Avoided Restrictions for Congestion Management, Voltage Control using Active Power (CMVCP)

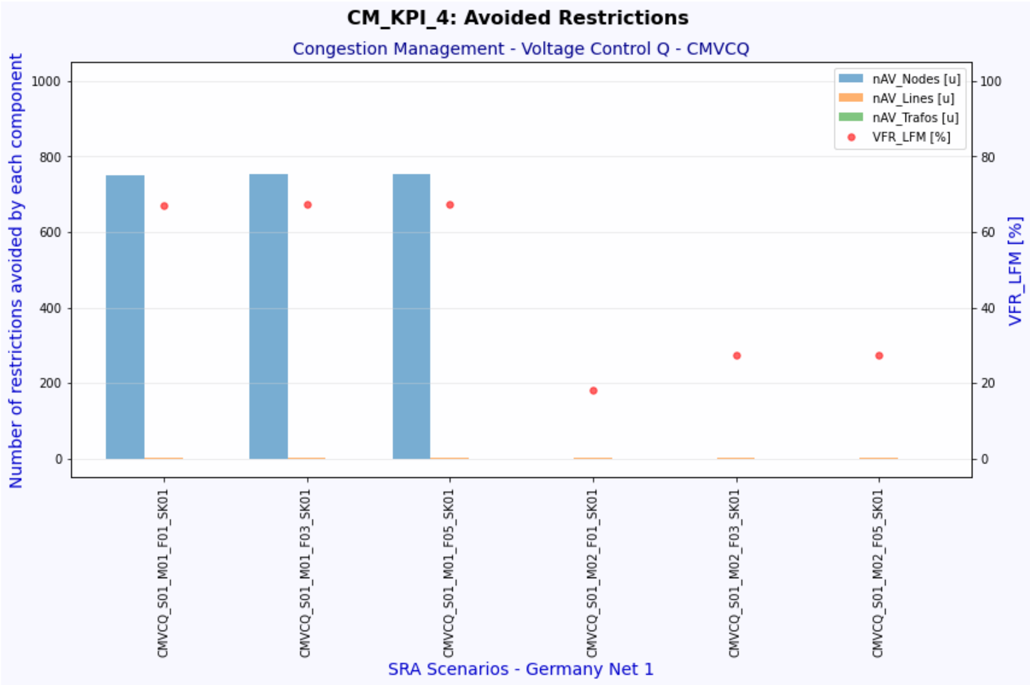


Figure 2.37 KPI CM_SPI_4: Avoided Restrictions, for Congestion Management, Voltage Control using Reactive Power (CMVCQ)

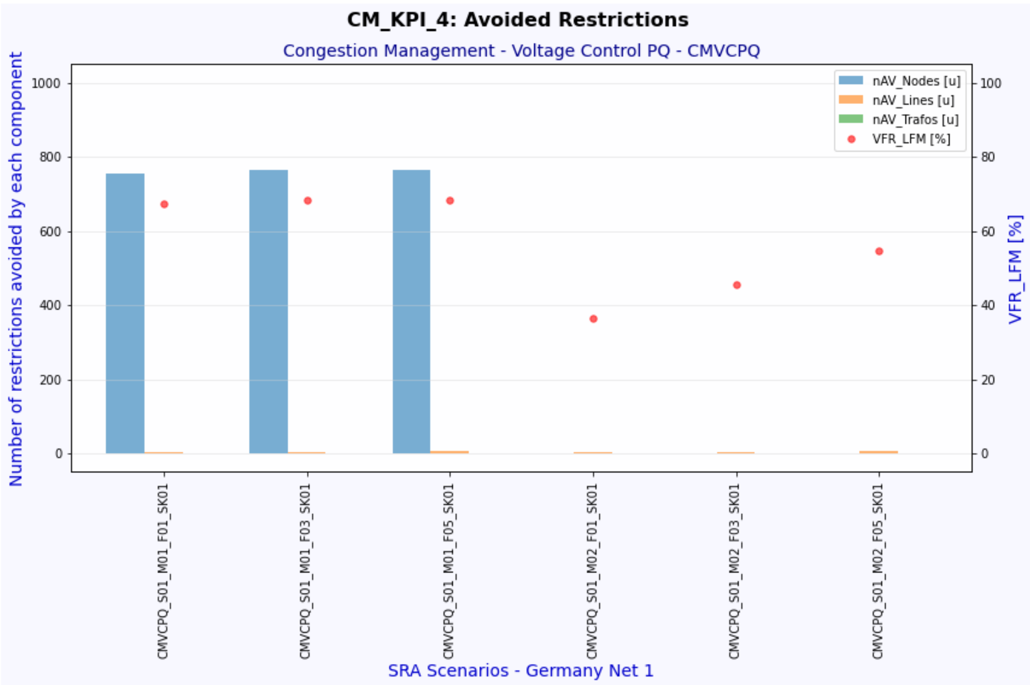
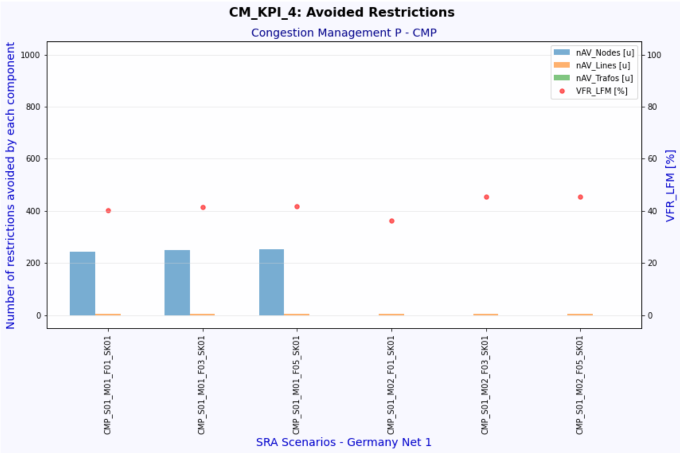
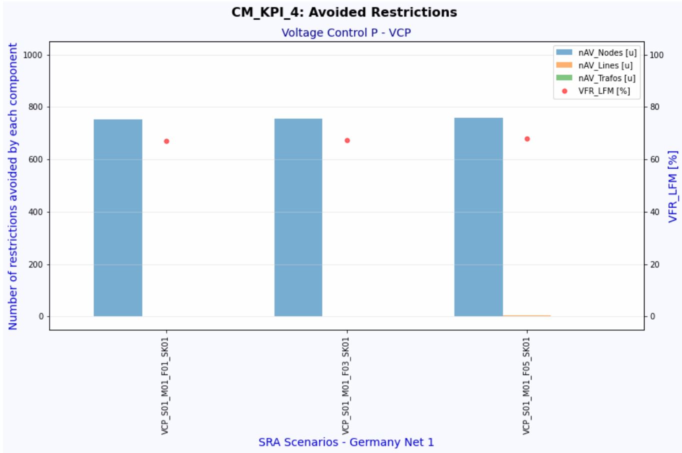


Figure 2.38 KPI CM_SPI_4: Avoided Restrictions for Congestion Management, Voltage Control using Active or Reactive Power (CMVCPQ)

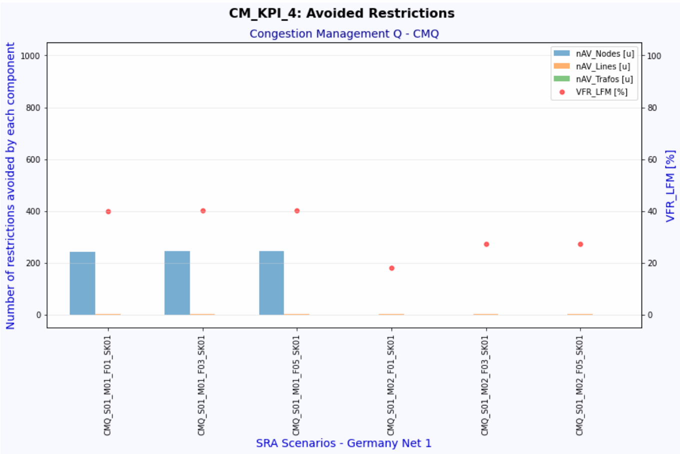
(a1)



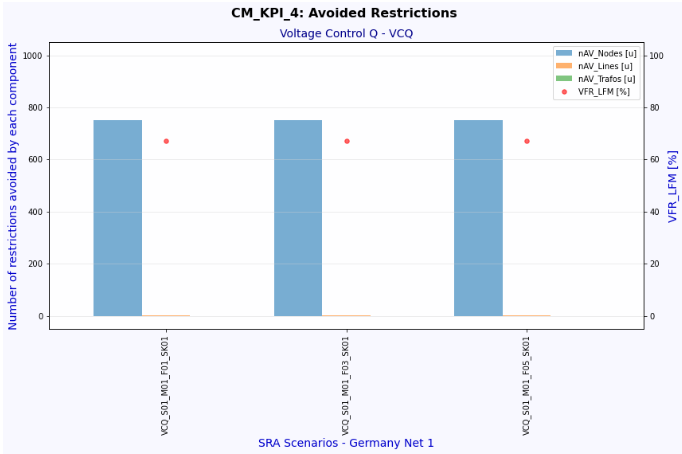
(b1)



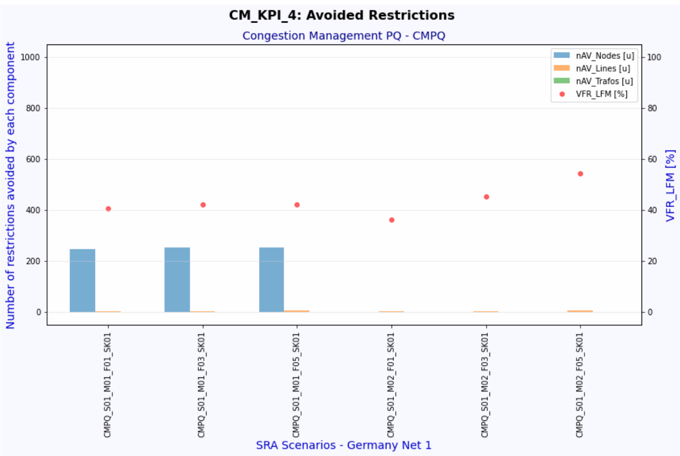
(a2)



(b2)



(a3)



(b3)

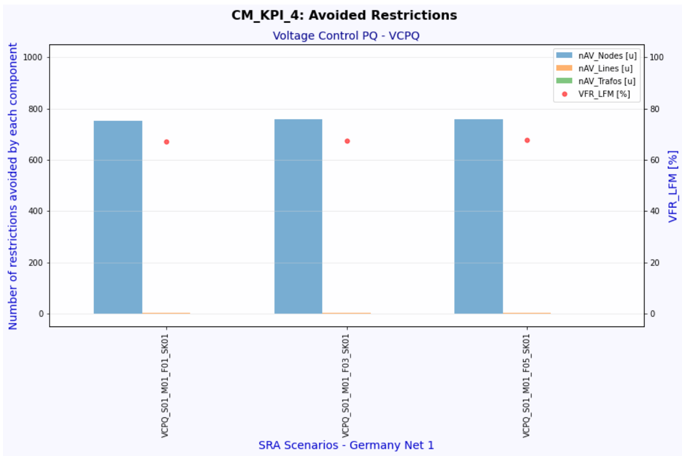


Figure 2.39 CM_KPI_4: Avoided Restrictions:
Congestion Management: a1) Active Power, a2) Reactive Power, a3) Active and Reactive Power.
Voltage Control: b1) Active Power, b2) Reactive Power, b3) Active and Reactive Power

2.3.2 SRA: DE-NET2-LV

2.3.2.1 Step 1: Input data

c) Network characteristics and load and generation profiles

Table 2.23 summarizes the input data for the DE-NET2-LV demo site. For this demo site, an anonymized MV-LV 20/0.4 kV grid was provided by the German demonstrator partners. Although this grid considers MV and LV levels, this SRA is focused on analyzing LV congested elements according to the definition of the demonstrator BUCs. Regarding the network elements, this grid consists of 2431 buses, 1952 lines, 24 secondary substations 20/0.4 kV, 831 load points, and 32 distributed generators (PV).

Similar to DE-NET1-LV, the load and generation profiles for DE-NET2-LV were defined on an hourly basis for a full year. Annual load profiles were provided by the German demonstrator partners, including typical profiles for household and commercial loads. Regarding electric heat storage loads, annual temperature-dependent profiles were built based on the registered temperature of the demo site obtained from [20] and normalized profiles for this type of load described in [21]. In the case of PV (photovoltaic), production profiles were built based on normalized profiles from the PVGIS database [20] and the location and installed capacity of PV plants.

Table 2.23 German demo site characteristics: DE-NET2-LV

Network ID	**DE-NET2-LV**
Network modelling	Anonymized grid provided by DSO
Grid level	MV-LV grid 20/0.4 kV, the SRA is focused on LV.
Network elements	2431 buses (263 MV), 1952 lines, 24 transformers, 831 load points (household, commercial, heat storage, heat pumps, industrial), 32 DGs (PV).
Load and Generation profiles	Yearly profiles (8760 hours) Load profiles data provided by DSO (household, commercial), year 2014. Heat storage, heat pumps, industrial load profiles; PV profiles based on literature information
FSPs	Selection of FSPs based on SRA scenarios: 58 FSPs (load and generation)

d) FSPs characteristics

Table 2.24 describes the FSPs considered in the DE-NET2-LV demo site. The selection of FSPs' location and quantity was defined according to the SRA Scenario 0 further described in the next subsection. In this scenario, congestion events are analyzed along the LV feeder of transformer T1022790 (20/0.4 kV), so all household load and generator elements connected to this feeder were chosen as FSPs. The flexibility costs information for active power was obtained from the Picloflex platform [15], and the reactive power flexibility cost was considered 5% of the active power bids cost assuming that the reactive power costs are due to the internal active power losses caused for the keeping the established reactive power set-point. [16]–[18]. Moreover, it should be noted that most of the FSPs offer upward and downward flexibility (active and reactive) except PV generators that don't provide active upward flexibility. For the SRA, we consider that each FSP has an available flexibility of 5% of its maximum capacity (base case). Based on the capability analysis of DERs operating curves, the value of 5% is also considered for reactive power bids [16].

Table 2.24 FSPs Characteristics, German demonstrator DE-NET2-LV

FSP ID	Bus ID	FSP type	Nominal capacity [MVA]	Active power upward capacity [%]	Active power downward capacity [%]	Active power upward cost [EUR/MWh]	Active power downward cost [EUR/MWh]	React. power upward capacity [%]	React. power downward capacity [%]	React. power upward cost [EU/MWh]	React. power downward cost [EU/MWh]
fsp1	1947	load	0.00453	5.00%	5.00%	39.98	39.96	5.00%	5.00%	2	2
fsp2	1826	load	0.00186			40.08	39.52			2	1.98
fsp3	2355	load	0.00352			39.73	39.8			1.99	1.99
fsp4	1824	load	0.00494			39.71	39.58			1.99	1.98
fsp5	1822	load	0.00582			39.46	39.54			1.97	1.98
fsp6	1831	load	0.00806			39.8	39.68			1.99	1.98
fsp7	1949	load	0.00370			39.62	39.82			1.98	1.99
fsp8	220	load	0.00494			39.77	39.93			1.99	2
fsp9	340	load	0.00587			39.4	39.74			1.97	1.99
fsp10	255	load	0.00469			39.58	39.9			1.98	2
fsp11	1750	load	0.00563			39.72	39.62			1.99	1.98
fsp12	948	load	0.00453			39.81	39.99			1.99	2
fsp13	1988	load	0.00436			39.46	39.58			1.97	1.98
fsp14	962	load	0.00587			39.84	39.96			1.99	2
fsp15	1871	load	0.00410			39.42	39.84			1.97	1.99
fsp16	1044	load	0.00293			39.63	39.62			1.98	1.98
fsp17	1203	load	0.03227			39.74	39.79			1.99	1.99
fsp18	1751	load	0.01935			39.89	39.8			1.99	1.99
fsp19	1937	load	0.00436			39.94	39.34			2	1.97
fsp20	2282	load	0.00655			40.17	39.33			2.01	1.97
fsp21	1448	load	0.01289			39.51	39.52			1.98	1.98
fsp22	2291	load	0.00292			39.87	39.61			1.99	1.98
fsp23	2271	load	0.00370			39.53	39.42			1.98	1.97
fsp24	1337	load	0.01490			39.37	39.41			1.97	1.97
fsp25	2224	load	0.00504			40.32	39.64			2.02	1.98
fsp26	1972	load	0.00402			39.55	39.97			1.98	2
fsp27	1072	load	0.00671			39.48	40.12			1.97	2.01
fsp28	1334	load	0.00410			39.57	39.63			1.98	1.98
fsp29	2295	load	0.00582			39.67	39.58			1.98	1.98
fsp30	943	load	0.00187			39.71	39.88			1.99	1.99
fsp31	1771	load	0.00187			40.22	39.91			2.01	2
fsp32	1752	load	0.06207			39.84	40.07			1.99	2
fsp33	183	load	0.01109			39.48	39.5			1.97	1.98
fsp34	1332	load	0.00408			39.98	40.29			2	2.01
fsp35	1756	load	0.01307			39.52	39.91			1.98	2
fsp36	1251	load	0.00422			39.88	39.83			1.99	1.99
fsp37	1638	load	0.00671			39.86	39.62			1.99	1.98
fsp38	1823	load	0.00601			39.72	39.33			1.99	1.97
fsp39	1825	load	0.00186			39.73	40.04			1.99	2
fsp40	1829	load	0.01307			39.66	39.77			1.98	1.99
fsp41	1176	load	0.00293			39.6	39.95			1.98	2
fsp42	1159	load	0.01094			40.03	39.92			2	2
fsp43	1936	load	0.00494			39.77	39.56			1.99	1.98
fsp44	1943	load	0.00617			40.55	39.41			2.03	1.97
fsp45	856	load	0.00370			39.53	39.84			1.98	1.99
fsp46	1421	load	0.01307			39.75	39.97			1.99	2
fsp47	1993	load	0.00453			39.62	40.05			1.98	2
fsp48	2274	load	0.02326			40.16	39.38			2.01	1.97
fsp49	2284	load	0.00621			39.39	38.75			1.97	1.94
fsp50	2288	load	0.00671			39.63	39.37			1.98	1.97
fsp51	2289	load	0.00186			39.69	39.88			1.98	1.99
fsp52	1361	load	0.00924			39.91	39.67			2	1.98

fsp53	2399	load	0.00186			39.94	39.29			2	1.96
fsp54	1448	gen	0.00297	0.00%		39.58	39.94			1.98	2
fsp55	1550	gen	0.00192			40.26	39.71			2.01	1.99
fsp56	2224	gen	0.00672			40.17	39.92			2.01	2
fsp57	1159	gen	0.00352			39.93	39.87			2	1.99
fsp58	1421	gen	0.0026			40.07	40.19			2	2.01

2.3.2.2 Step 2: SRA scenarios

The DE-NET2-LV network is analyzed under the conditions of Scenario 0, i.e., considering the initial load and generation annual profiles described in the previous subsection. The quantitative SRA methodology is applied for this scenario and the results are further analyzed in the following subsections considering the SRA parameters and KPIs of Table 2.25.

Table 2.25 SRA scenarios for the German demonstrator DE-NET2-LV

Scenario ID	Description	SRA parameters	KPIs
Scenario 0	Initial yearly profiles	Load scaling up, FSPs bid size, Bus voltage limits	EU_KPI_1: Increased RES and DER hosting capacity EU_KPI_2: Increase of energy storage solutions penetration CM_KPI_4: Avoided restrictions

2.3.2.3 Step 3: LFM model

a) SRA Scenario 0

This scenario examines the congestion events in the network under the conditions of Scenario 0 described previously. The results are described below for each step of the SRA methodology.

- **Flexibility needs calculation (Step 3.1):** Considering the new load profiles, a power flow analysis is run for 8760 hours to identify potential constraints. Figure 2.40, Figure 2.41, and Figure 2.42 display results for lines loading, transformers loading, and bus voltage magnitude, respectively. From Figure 2.41, we identified that transformer T1022790 is congested, and from Figure 2.29Figure 2.42 we can observe that some buses have undervoltage values (below 0.95 p.u.). By contrast, Figure 2.40 shows that lines are not congested in this scenario.

  Considering power flow results, the corresponding flexibility needs are computed. Table 2.26 summarizes scenario 0 flexibility needs and network issues associated with congestion management and voltage control, resulting in 32 congestion problems and 1303 voltage violations. These values are determined by considering the number of congested elements multiplied by the hours when these problems occur.

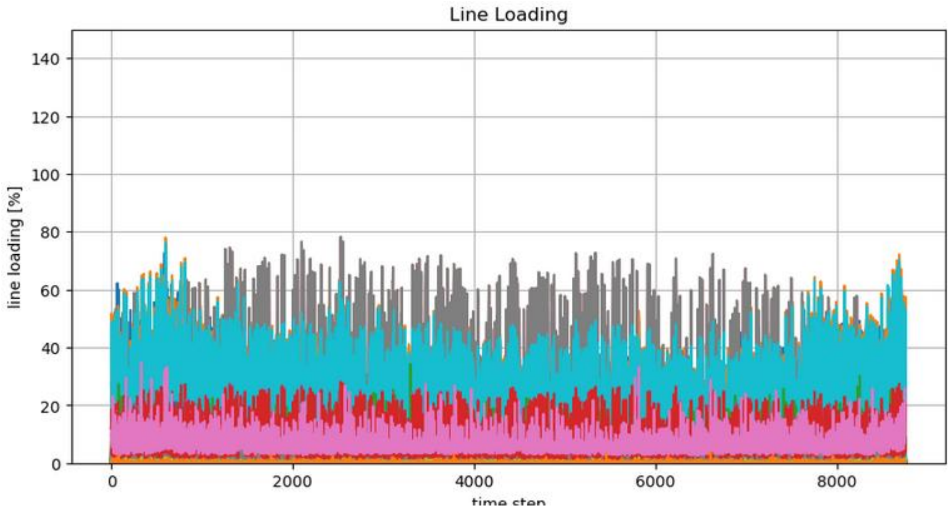


Figure 2.40 Lines loading [%] for the Scenario 0, DE-NET2-LV

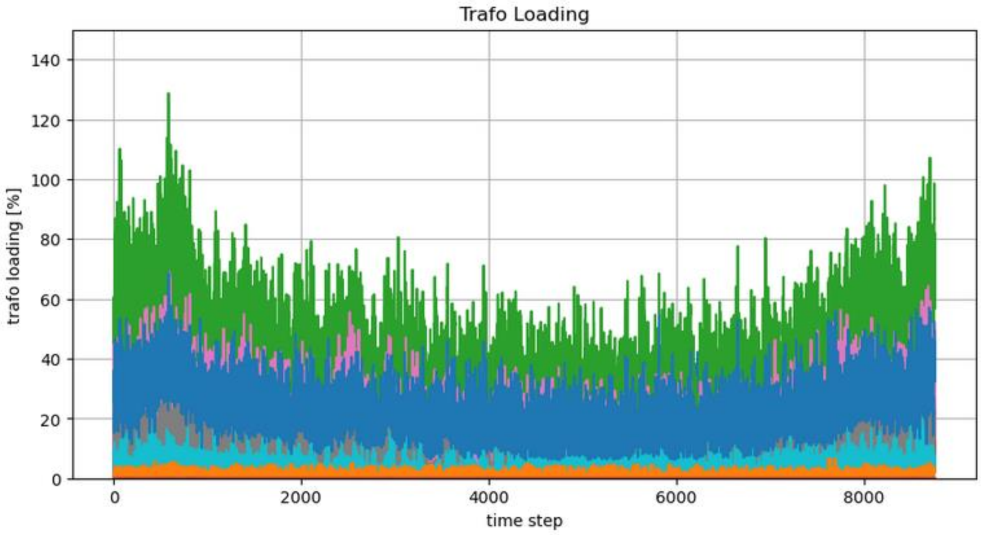


Figure 2.41 Transformer loading [%] for the Scenario 0, DE-NET2-LV

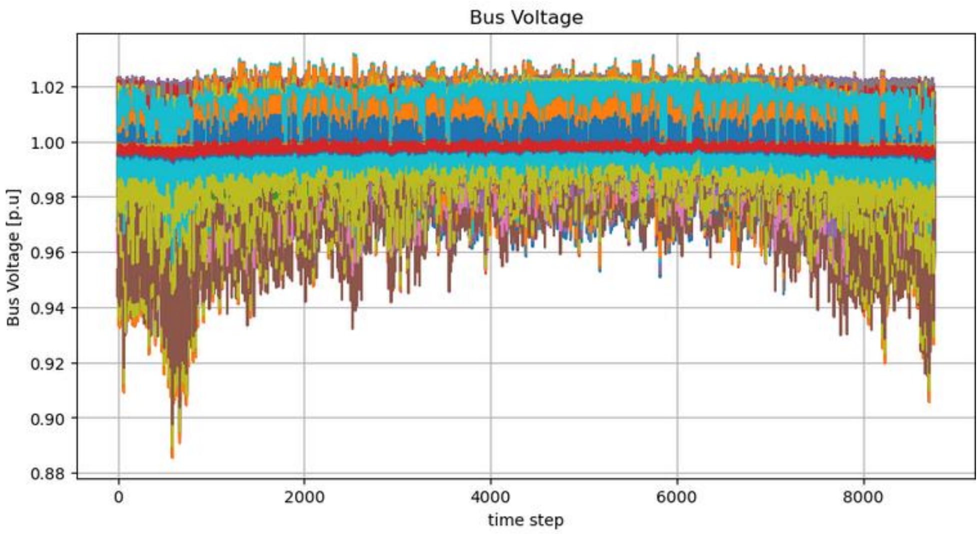


Figure 2.42 Bus Voltage [p.u.] for the Scenario 0, DE-NET2-LV

Table 2.26 Summary of Flexibility Needs for DE-NET2-LV

Congestion management and voltage control flexibility needs	Value
Congested lines and/or transformers	Trafo T1022790
Total congestion problems (congested elements by hours)	32
Overvoltage problems (bus with overvoltage by hours)	0
Undervoltage problems (bus with undervoltage by hours)	1303

- **Sensitivity factors calculation (Step 3.2):** In this step, sensitivity factors are computed for each FSP participating in the local market relative to the flexibility needs obtained in the previous step. Table 2.27 and Table 2.28 summarize the resulting sensitivity factors for congestion management and voltage control, respectively. It should be emphasized that the sensitivity factors have been computed for each hour of study (hours with congestion events in lines, transformers, or buses). For simplicity, the values shown in both tables correspond to the mean ± standard deviation of all hourly values obtained by each type of FSP.

  Regarding congestion management, Table 2.27 indicates that changes in active power (P) and reactive power (Q) in all FSPs impact the apparent power (S) of transformer T1022790 with factors very close to unity in the case of P (column 1), and with smaller factors in the case of Q (column 2). The negative sign of the sensitivity factors implies an inverse relationship, which means that an increase in P or Q in FSP results in a decrease in the S value of the congested element.

  With regards to voltage control, Table 2.28 provides an example of computed sensitivity factors for buses with the highest and the lowest voltage magnitude p.u in the pre-market. It can be observed that both active and reactive power injections from FSP 35 impact on nodes 1756 (lowest) and 17 (highest), while the rest of FSPs have no influence on these nodes.

Table 2.27 Sensitivity factors for congestion management, DE-NET2-LV ([11])

FSP ID	FSP type	Sensitivity factors T1022790 dS/dP	Sensitivity factors T1022790 dS/dQ
fsp1 to fsp53	Load	-1.096 ± 2.67e-09	-0.439 ± 2.02e-09
Fsp54 to fsp58	Generation	-1.096 ± 2.68e-09	-0.422 ± 1.99e-09

Table 2.28 Sensitivity factors for voltage control, DE-NET2-LV ([12])

FSP ID	FSP type	Sensitivity factors Bus 1756	Sensitivity factors Bus 17

[11] Sensitivity factors have been computed for each hour of study. For simplicity, the reported values correspond to the mean ± standard deviation of the all hourly values obtained.

[12] Sensitivity factors have been computed for each hour of study. For simplicity, the reported values correspond to the mean ± standard deviation of the all hourly values obtained.

		(Lowest Value - premarket) dV/dP	(Highest Value - premarket) dV/dQ
fsp1 to fsp34 and fsp36 to fsp53	Load	0	0
fsp35		2.002 ± 6.52e-11	2.016 ± 9.53e-11
Fsp54 to fsp58	Generation	0	0

- **FSP's bid generation (Step 3.3):** This step computes the flexibility limit that each FSP can provide, both downward and upward, for active and reactive power, based on its characteristics provided in Table 2.24 and the network operational conditions established in Scenario 0.
- **Local flexibility market-clearing (Step 3.4) and post-evaluation (Step 3.5):** In step 3.4, a local flexibility market-clearing is carried out to solve the criticalities identified in step 3.1 using the most efficient flexibility bids from FSPs (step 3.3) at minimum cost. The LFM clearing considers the sensitivities factors computed in step 3.2 as a representation of the network constraints. To evaluate the SRA performance of scenario 0, sensitivities are applied according to Table 2.29. Furthermore, it should be emphasized that a cost of 12410 (EUR/MWh) is considered for the $VOLL$ parameter in the German demonstrator according to reference [19].

Table 2.29 Sensitivities to the SRA parameters for Scalability, Scenario 0, DE-NET2-LV

Parameter	Parameter description	Sensitivity Range
M02, M03	Limits of maximum and minimum permissible voltage levels for buses	$M0x = [v_{min}, v_{max}]$ $M02 = [0.93, 1.07]$ $M03 = [0.90, 1.10]$
F01, F03, F05	Increase in available flexibility from FSPs	*F0x* = [5%, 15%, 25%]
SK01	Increase in storage capacity.	*SK0x* = [Nominal Capacity]

As mentioned before, the selected BUCs for the quantitative SRA of the German demonstrator are focused on the development of LFMs for Congestion Management and Voltage Control utilizing active power (CMVCP) and reactive power (CMVCQ). Therefore, Table 2.30 and Table 2.31 summarize the SRA results obtained for these two cases considering the SRA scenarios and sensitivities described before. In both tables, the cost of the Objective Function equals the sum of the costs of the total active and reactive power FSP's bids cleared in the market plus the cost of the auxiliary variables Alpha and Beta, which implies that the model has been satisfactorily solved. Alpha represents the cost of the flexibility not supplied by the Voltage Control component while Beta corresponds to the cost of the flexibility not supplied by the Congestion Management component[13]. As the capacities of the FSPs increase (from F01 to F05), the associated costs of Alpha and Beta decrease. Given the high costs attributed to these factors, their reduction aligns with the model's objective to minimize total costs. Furthermore, it can be noted that under conditions with lower voltage boundary

[13] A comprehensive description of Alpha and Beta can be found in the LFM formulation of Annex II.

constraints (specifically M03 in comparison to M02), there is a remarkable reduction of Alpha cost.

It should be noted that in the case of CMVCP, there are no costs associated with reactive power. Similarly, in the case of CMVCQ, the active power cost is zero. This logical result arises from the fact that these types of offers compete exclusively in their respective markets. Additionally, Table 2.32*Table 2.22* presents SRA results obtained by considering a LFM model for Congestion Management and Voltage Control, where both active and reactive power are simultaneously taken into account. It can be seen that this model achieves a greater reduction in total costs compared to the two previous cases, potentially due to a lower unsupplied flexibility.

Table 2.30 Summary of costs resulting from the market clearing for congestion management and voltage control with active power, Scenario 0, DE-NET2- LV

Scenario	Objective Value [EUR]	Beta Cost [EUR]	Alpha Cost [EUR]	Total Active Power [MW]	Active Power Cost [EUR]	Total Reactive Power [MVAR]	Reactive Power Cost [EUR]
CMVCP_S01_M02_F01_SK01	145841,24	1520,37	144306,97	0,35	13,74	-	-
CMVCP_S01_M02_F03_SK01	138091,95	245,00	137812,34	0,86	34,05	-	-
CMVCP_S01_M02_F05_SK01	132803,98	27,77	132725,89	1,25	49,51	-	-
CMVCP_S01_M03_F01_SK01	3949,06	1520,37	2423,40	0,13	5,29	-	-
CMVCP_S01_M03_F03_SK01	2498,66	245,00	2245,07	0,21	8,45	-	-
CMVCP_S01_M03_F05_SK01	2164,95	27,77	2128,16	0,22	8,88	-	-

Table 2.31 Summary of costs resulting from the market clearing for congestion Management and voltage control with reactive power, Scenario 0, DE-NET2- LV

Scenario	Objective Value [EUR]	Beta Cost [EUR]	Alpha Cost [EUR]	Total Active Power [MW]	Active Power Cost [EUR]	Total Reactive Power [MVAR]	Reactive Power Cost [EUR]
CMVCQ_S01_M02_F01_SK01	151298,28	3409,92	147888,34	-	-	0,01	0,02
CMVCQ_S01_M02_F03_SK01	151220,18	3336,13	147884,01	-	-	0,02	0,04
CMVCQ_S01_M02_F05_SK01	151153,11	3273,36	147879,67	-	-	0,03	0,07
CMVCQ_S01_M03_F01_SK01	5929,42	3409,92	2519,48	-	-	0,01	0,02
CMVCQ_S01_M03_F03_SK01	5855,66	3336,13	2519,48	-	-	0,02	0,04
CMVCQ_S01_M03_F05_SK01	5792,92	3273,36	2519,48	-	-	0,03	0,07

Table 2.32 Summary of resulting costs from the market clearing for congestion management and voltage control with active and reactive power, Scenario 0, DE-NET2- LV

Scenario	Objective Value [EUR]	Beta Cost [EUR]	Alpha Cost [EUR]	Total Active Power [MW]	Active Power Cost [EUR]	Total Reactive Power [MVAR]	Reactive Power Cost [EUR]
CMVCPQ_S01_M02_F01_SK01	144495,85	1331,72	143150,41	0,34	13,48	0,12	0,23
CMVCPQ_S01_M02_F03_SK01	135351,27	188,61	135130,18	0,80	31,92	0,28	0,55
CMVCPQ_S01_M02_F05_SK01	129170,84	0,00	129170,84	1,15	45,70	0,38	0,76
CMVCPQ_S01_M03_F01_SK01	3729,65	1331,55	2392,97	0,13	5,03	0,05	0,10
CMVCPQ_S01_M03_F03_SK01	2382,57	188,60	2186,52	0,18	7,28	0,08	0,16
CMVCPQ_S01_M03_F05_SK01	2084,55	0,00	2076,89	0,19	7,47	0,10	0,19

To enhance the understanding of the SRA results, Figure 2.43, Figure 2.44, and Figure 2.45 show the number of occurrence plots of all bus voltages [p.u.], before (pre) and after (post) the market, for CMCVP, CMCVQ, and CMCVPQ, across each considered scenario. Moreover, the bar plots display the changes in voltage violations for each scenario. Similarly, Figure 2.46, Figure 2.47, and Figure 2.48 present number of occurrence plots illustrating the load percentage of transformers, while the corresponding bar graphs specifically highlight the transformers experiencing congestion problems.

From the voltage plots, it can be seen that as the size of the FSPs increase (from F01 to F05), bus voltages tend to converge within the voltage limits compared to the pre-market conditions. The bar plots show that in M02 cases, the undervoltage problems that were present before the market significantly decrease. Comparing the impacts of CMVCP, CMVCQ, and CMVCPQ model markets, for M02, it can be observed that the latter achieves a remarkable reduction in undervoltage problems as FSPs size increase. In the case of scenario M02, there are not important issues to be considered, but there has been an improvement in bus voltages by shifting to the centre of the plots.

Similar behavior can be observed in the graphs depicting the transformer overloading, where the number of occurrence plot moves closer to the maximum thermal limit as the size of the FSPs increase. Notably, the CMVCPQ market model consistently achieves better results compared to CMVCP and CMVCQ in terms of congestion management. Interestingly, when considering only the use of reactive power for congestion management, increasing the capacity of FSPs to provide reactive power does not seem to effectively solve congestion problems. This suggests that the utilization of reactive power alone may not be sufficient to mitigate congestion effectively.

.

(a) (b)

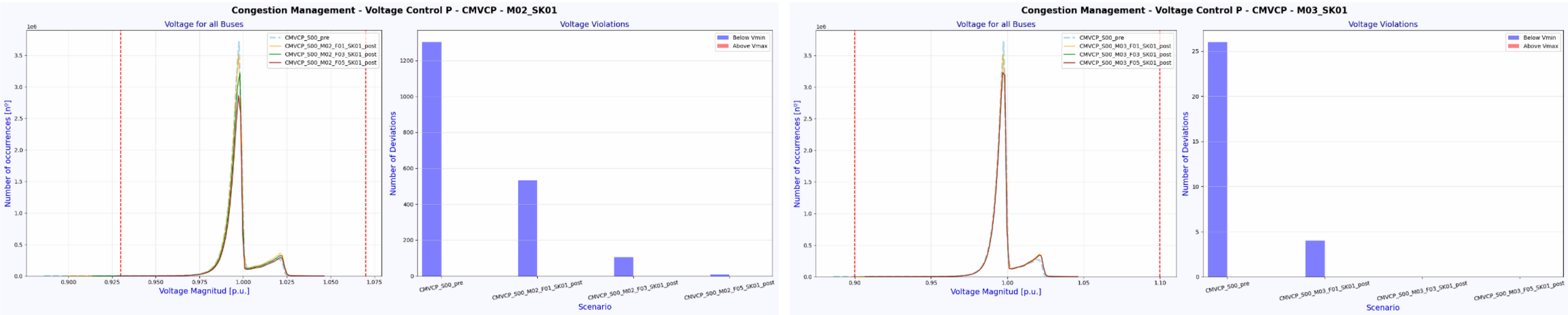


Figure 2.43 Deviation plots for Voltage Magnitude [p.u.] obtained from Congestion Management – Voltage Control with Active Power (a) Scenario M02, (b) Scenario M03. Scenario 0, DE-NET2-LV.

(a) (b)

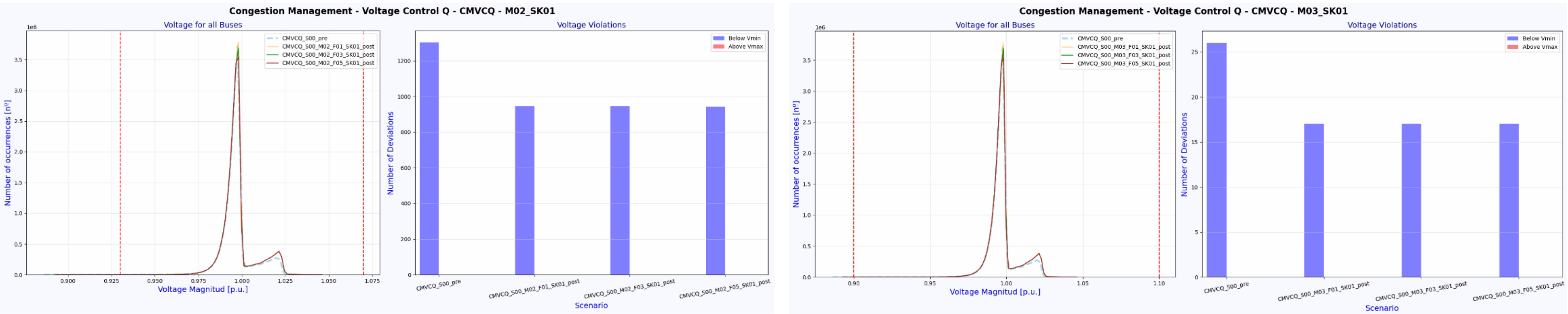
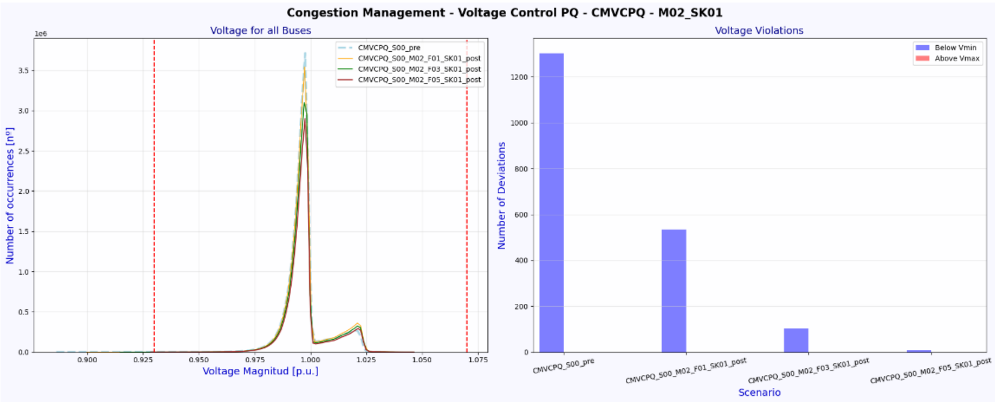


Figure 2.44 Deviation plots for Voltage Magnitude [p.u.] obtained from Congestion Management – Voltage Control with Reactive Power (a) Scenario M02, (b) Scenario M03. Scenario 0, DE-NET2-LV.

(a)



(b)

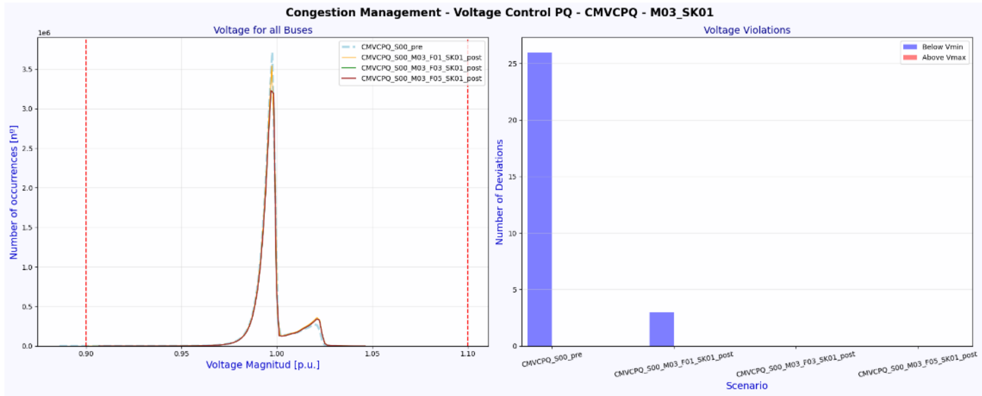


Figure 2.45 Deviation plots for Voltage Magnitude [p.u.] obtained from Congestion Management – Voltage Control with Active and Reactive Power (a) Scenario M02, (b) Scenario M03. Scenario 0, DE-NET2-LV.

(a) (b)

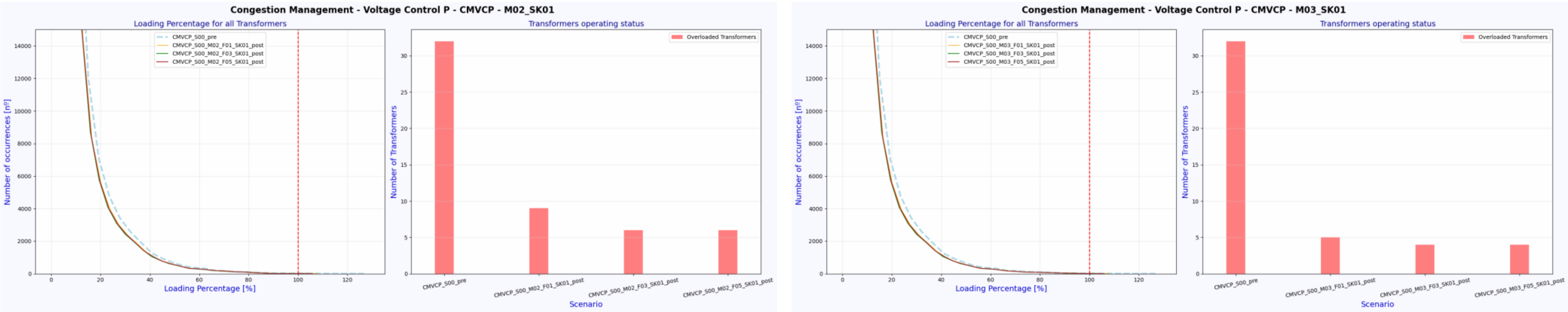


Figure 2.46 Deviation plots for Loading Percentage [%] of all Transformers obtained from Congestion Management – Voltage Control with Active Power (a) Scenario M02-K01, (b) Scenario M03-K01. Scenario 0, DE-NET2-LV.

(a) (b)

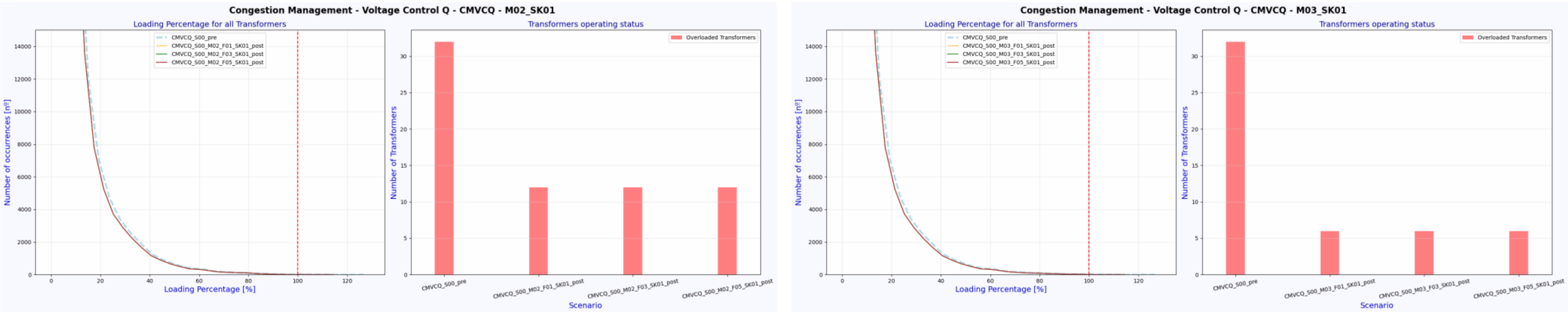


Figure 2.47 Deviation plots for Loading Percentage [%] of all Transformers obtained from Congestion Management – Voltage Control with Reactive Power (a) Scenario M02-K01, (b) Scenario M03-K01. Scenario 0, DE-NET2-LV.

(a) (b)

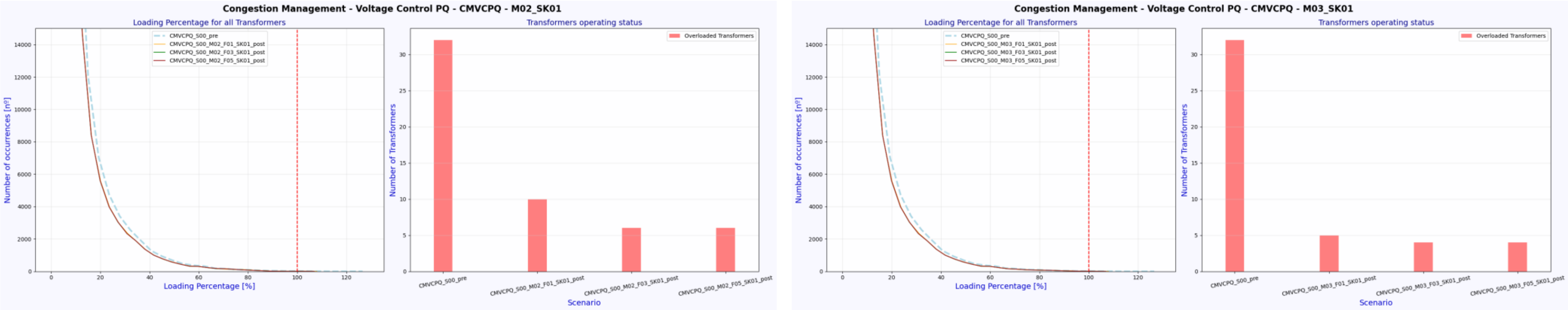


Figure 2.48 Deviation plots for Loading Percentage [%] of all Transformers obtained from Congestion Management – Voltage Control with Active and Reactive Power (a) Scenario M02-K01, (b) Scenario M03-K01. Scenario 0, DE-NET2-LV.

2.3.2.4 Step 4: KPIs calculation

This KPI quantifies the number of criticalities that the market models have resolved. In this case, the SRA is focused on the reduction of transformer congestions and bus voltage violations. Figure 2.49 and Figure 2.50 display the results of all SRA parameters for CMVCP and CMVCQ, respectively. Figure 2.51 serves as a comparative analysis, examining how the market dynamics are modified when active and reactive power are used simultaneously in the CMVCPQ market model. The different scenarios are plotted along the horizontal axis, while the vertical axes display, on the left side, the number of restrictions avoided in each component (Nodes, Lines, and Transformers), and on the right side, the Violation Frequency Reduction of the LFM (VFR_LFM) presented as a percentage (red dots).

Finally, it is important to note that other market models have been considered to analyze their impact on the grid. Figure 2.52 depicts the results obtained for this KPI using only Congestion Management (CM) or Voltage Control (VC).

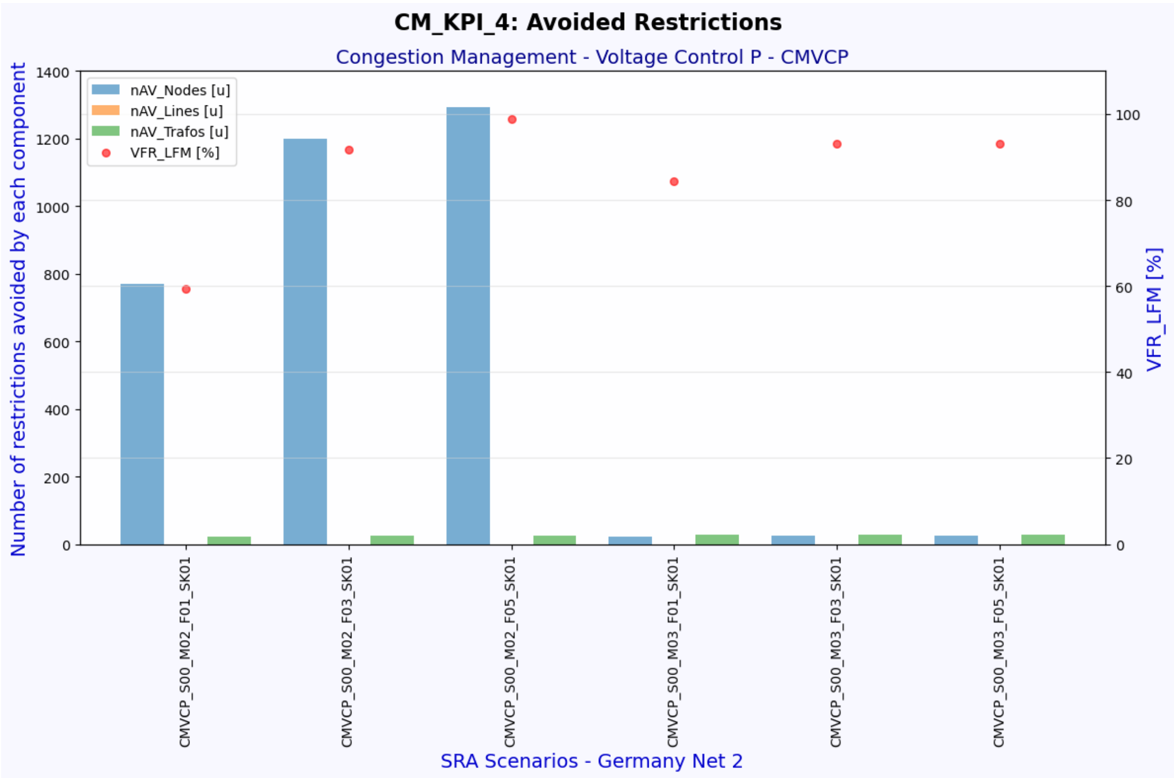


Figure 2.49 KPI CM_SPI_4: Avoided Restrictions for Congestion Management, Voltage Control using Active Power (CMVCP)

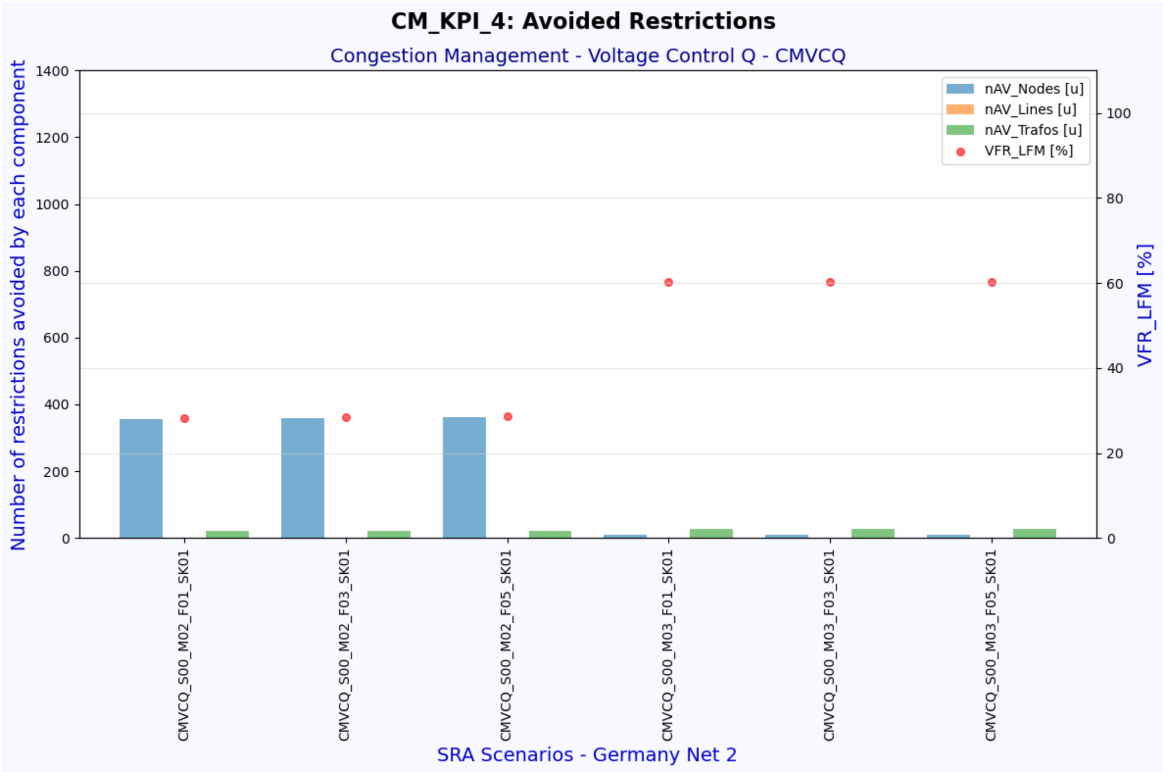


Figure 2.50 KPI CM_SPI_4: Avoided Restrictions for Congestion Management, Voltage Control using Reactive Power (CMVCQ)

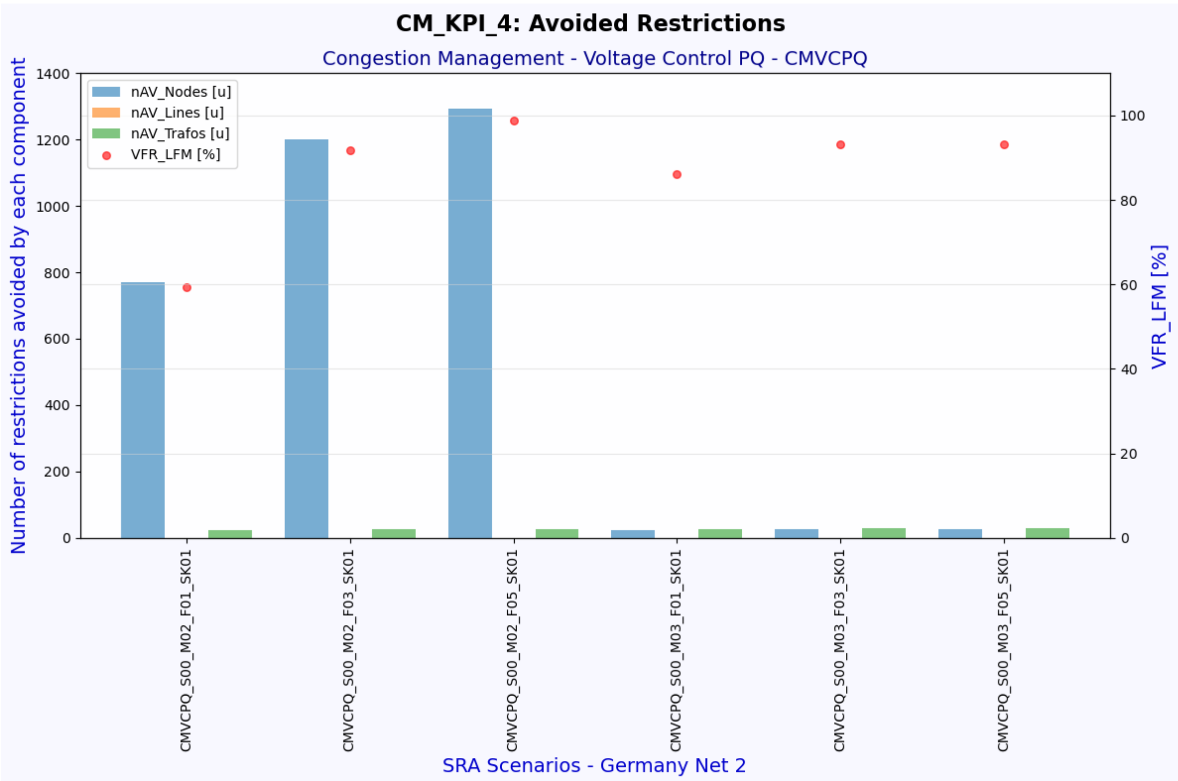
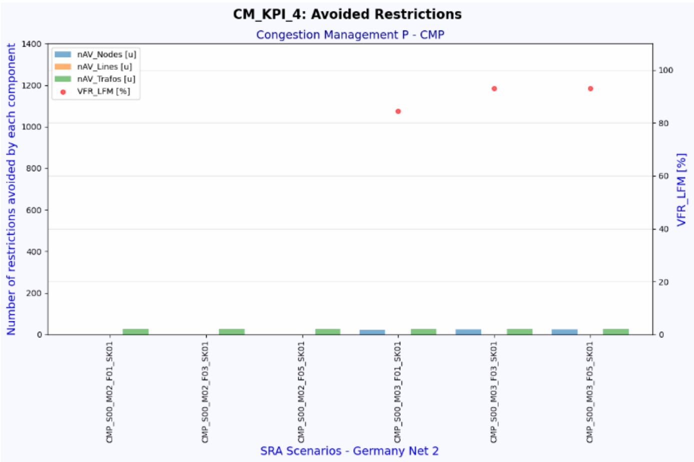
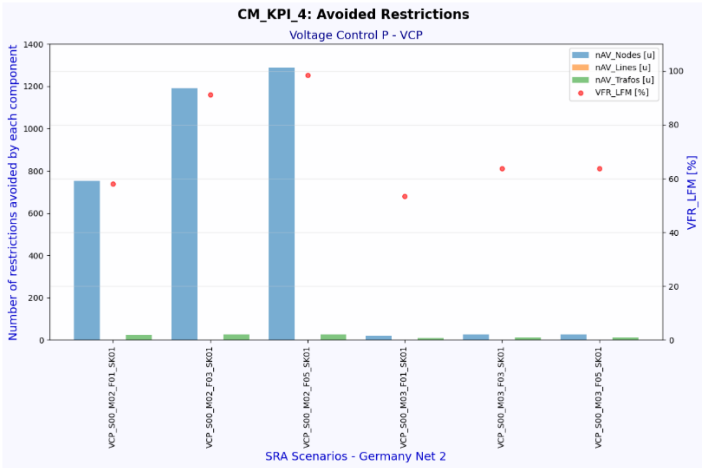


Figure 2.51 KPI CM_SPI_4: Avoided Restrictions for Congestion Management, Voltage Control using Active or Reactive Power (CMVCPQ)

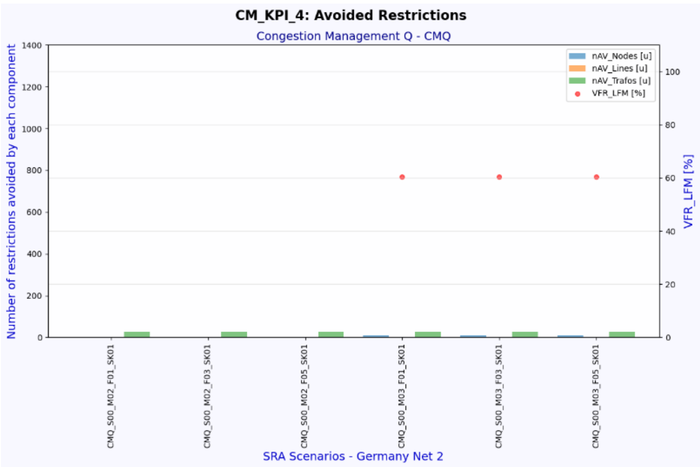
(a1)



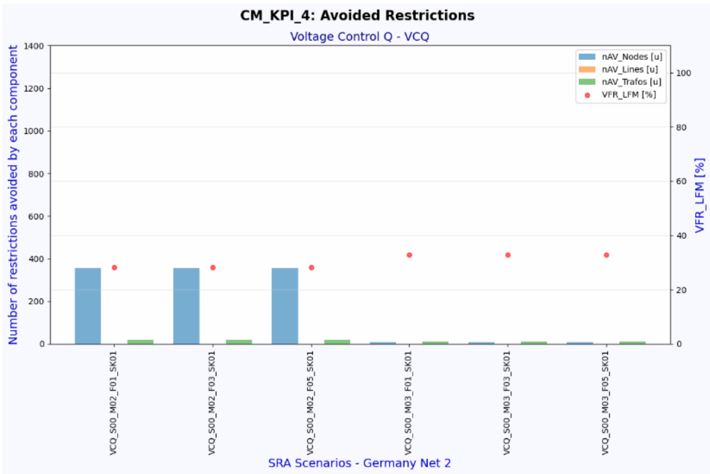
(b1)



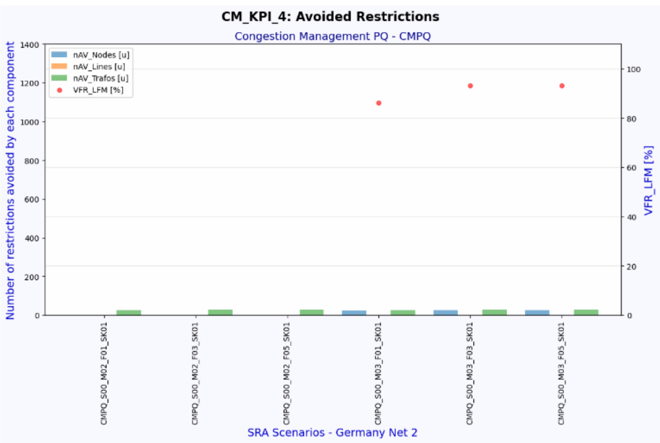
(a2)



(b2)



(a3)



(b3)

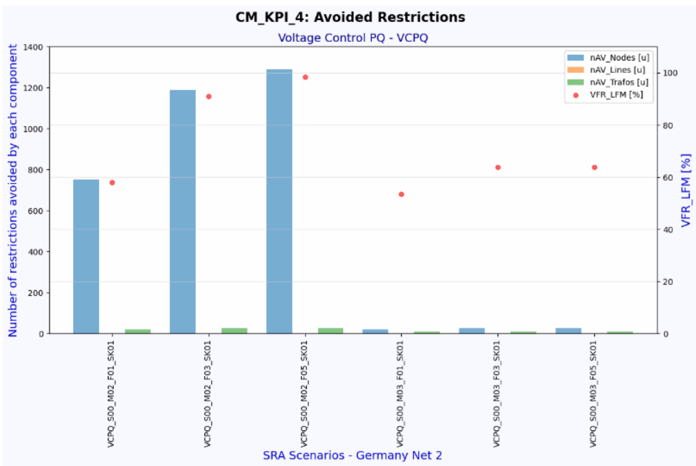


Figure 2.52 CM_KPI_4: Avoided Restrictions:
Congestion Management: a1) Active Power, a2) Reactive Power, a3) Active and Reactive Power.
Voltage Control: b1) Active Power, b2) Reactive Power, b3) Active and Reactive Power

2.3.3 Interim conclusions

For the SRA of the German demonstrator, two demo sites were selected. These sites, DE-NET1-LV and DE-NET2-LV, share similar characteristics in terms of voltage level and number of grid elements. However, their main point of distinction lies in their type of loads. In DE-NET1-LV, the predominant loads are from single-family households. On the other hand, DE-NET2-LV comprises a combination of large apartment buildings and single-family households with a high density of installed power. A relevant aspect of these demo sites is the utilization of night electrical heat storage equipment.

From the SRA results of the DE-NET1-LV, it can be concluded that:

- For DE-NET1-LV two SRA scenarios were tested. Scenario 0 considers the initial load and generation annual profiles, resulting in no congested elements. Furthermore, Scenario 1 examines the congestion events in the network under the Scenario 0 conditions, but the consumption of load elements connected to the LV feeder of transformer T0 (20/0.4 kV) was increased by 25%. The focus is on this feeder as its elements were identified as being closest to congested during the Scenario 0 assessment. In the SRA Scenario 1, the flexibility needs involve two main criticalities that are identified in some hours of the winter time, i) The overloading of one LV line (L23), which is part of the LV network of T0, and ii) Undervoltage problems in some buses located downstream of T0. Moreover, for the SRA purpose 50 FSPs (most of them are PV and flexible loads connected at the same household) are considered in this demo site, and all of them are located in the T0 LV network. A summary of flexibility needs, FSP's characteristics, and the corresponding sensitivity factors were provided in subsection 2.3.1.3.

- The SRA results of Scenario 1 show that the LFM models for congestion management and voltage control with active power (CMVCP) and reactive power (CMVCQ) have shown proficiency in reducing network criticalities compared to the pre-market results. According to Figure 2.30 to Figure 2.35, in M01-based scenarios, voltage violations have shown significant reductions, decreasing from 1113 pre-market to a range of 362 to 353 post-market. Furthermore, line congestion problems have also decreased from 11 issues pre-market to a range of 9 to 6 post-market.

- Furthermore, the SRA results demonstrate that the procurement of flexibility through a LFM focused on both congestion management and voltage control services and using active and reactive power (CMVCPQ) outperforms the CMVCP or CMVCQ models in terms of avoided restrictions and the overall cost of the solution. However, when the capacity of FSPs is increased from F01 to F03 and F05, the markets' ability to improve further avoided restrictions becomes limited. These results are because most of the criticalities arise from the use of night electrical heat storage and only FSPs type load (50% of FSPs) can solve these problems in this demo site under the SRA conditions of this report. Therefore, more resources are needed to provide flexibility during night hours, such as batteries or DSO own resources such as network reconfiguration, control of OLTCs, etc.

- Finally, additional market models have been examined to assess their impact on the network, considering different scenarios involving Congestion Management (CM) or Voltage Control (VC) exclusively, with Active Power, Reactive Power, or both. The results reveal that each market model directly influences its related criticality. For instance, CM effectively reduces congestion on lines, while VC improves voltage levels in the buses. However, it is important to note that these actions may also have an impact on the other criticality in the opposite manner.

From the SRA results of the DE-NET2-LV, it can be concluded that:

- The flexibility needs of this demo site involve two issues that occur during certain hours in December and January. These issues are related to the overloading of a MV/LV transformer and undervoltage problems in some buses located downstream of the congested transformer (SRA Scenario 0).

- Similar to the DE-NET1-LV demo site, the SRA results in DE-NET2-LV show that the procurement of flexibility through a LFM focused on both congestion management and voltage control services and using active and reactive power (CMVCPQ) outperforms the CMVCP or CMVCQ models in terms of avoided restrictions and the overall cost of the solution.

- In addition, it is worth mentioning that additional market models have been explored in the SRA of the DE-NET2-LV with a specific focused on only congestion management or only voltage control. The results of VC models are similar to the join models of CMVC in terms of their effectiveness in avoiding restrictions. By contrast, the results of the CM models were found to be less favorable when compared to the VC and CMVC models. This implies that the same FSPs that solve bus voltage violations can reduce the loading of the transformer studied in this SRA scenario, but the FSPs' bids cleared in the CM market models do not contribute to solving bus voltage issues. Therefore, for installing new FSPs, the FSP's location is a relevant parameter to be selected based on both the expected lines/trafos congestions and bus voltage violations.

- According to results shown in Figure 2.46, Figure 2.47, and Figure 2.48, the procurement of flexibility has proven effective in mitigating congestion issues within the studied transformer when compared to pre-market conditions. However, when the capacity of FSPs is increased from F01 to F03 and F05 the market's ability to improve further avoided restrictions becomes limited. These results are due to the fact that most of the congestion problems in the transformer arise from the use of night electrical heat storage, and only FSPs type load can solve these problems. A remarkable difference between DE-NET1 and DE-NET2 is that the later has more capacity in terms of FSPs type load, therefore, more criticalities are solved in the DE-NET2 demo site.

2.4 Portuguese demonstrator quantitative SRA

This subsection aims to present and analyze the quantitative SRA results of the Portuguese demonstrator, with a specific focus on the PT-NET1-MV-LV demo site. The selection of this demo site was determined earlier in the chapter, as explained in the EUniversal SRA approach (refer to Table 2.1). This network was selected because both MV and LV flexibility needs can be analyzed, and it has different types of FSPs, such as MV loads, LV household loads, LV PV generation, and LV storage. It is important to note that the content of this subsection follows the four steps proposed in the quantitative SRA methodology, providing details of the input data, SRA scenarios, LFM model, and KPIs results.

2.4.1 SRA: PT-NET1-MV-LV

2.4.1.1 Step 1: Input data

a) Network characteristics and load and generation profiles

Table 2.33 summarizes the input data for the PT-NET1-MV-LV demo site. The SRA is focused on a MV feeder that is fed by a 60/15 kV substation, which consists of 1602 buses, 800 lines, 38 secondary substations 15/0.4 kV, 326 load points (26 MV clients), 18 distributed generators (PV), and 4 batteries. It is important to highlight that this feeder is part of an anonymized MV-LV 60/15/0.4 kV grid provided by Portuguese demonstrator partners.

For this demo site, load and generation profiles were defined on an hourly basis for a full year, i.e., for 8760 operation points. In the case of PV (photovoltaic), production profiles were built based on normalized profiles from the PVGIS database [20] and the location and installed capacity of PV plants. Regarding MV and LV loads, they are assigned typical profiles derived from data provided by the Portuguese Energy Services Regulatory Authority (ERSE) [22] and according to their annual consumption and voltage level.

Table 2.33 Portuguese network considered in the EUniversal SRA

Network ID	**PT-NET1-MV-LV**
Network modelling	Anonymized grid provided by the DSO
Grid level	MV-LV grid 15/0.4 kV
Network elements	1602 buses, 800 lines, 38 transformers, 326 load points (household LV, MV loads, and aggregated secondary substations loads), 18 DGs (PV in LV), 4 storage.
Load and Generation profiles	Yearly profiles (8760 hours) Load profiles based on BTNA-B-C ERSE profiles, and depending of annual consumption of load points. PV profiles based on PVGIS information.
FSPs	Selection of FSPs based on D7.1 information: 24 FSPs (load, generation, and storage)

b) FSPs characteristics

Table 2.34 describes the FSPs considered in the PT-NET1-MV-LV demo site. The selection of FSPs' location and quantity was defined according to the information reported in the EUniversal D7.1 [5]. The flexibility costs information for active power was obtained from the Picloflex platform [15], and the reactive power flexibility cost was considered 5% of the active power bids cost assuming that the reactive power costs are due to the internal active power losses caused for the keeping the established reactive power set-point. [16]–[18]. Moreover, it should be noted that most of the FSPs offer upward and downward flexibility (active and reactive) except PV generators that don't provide active upward flexibility. For the SRA, we consider that each FSP has an available flexibility of 5% of its maximum capacity (base case). Based on the capability analysis of DERs operating curves, the value of 5% is also considered for reactive power bids [16].

Table 2.34 FSPs Characteristics, Portuguese demonstrator

FSP ID	Bus ID	FSP type	Nominal capacity [MVA]	Active power upward capacity [%]	Active power downward capacity [%]	Active power upward cost [EU/MWh]	Active power downward cost [EU/MWh]	React. power upward capacity [%]	React. power downward capacity [%]	React. power upward cost [EU/MWh]	React. power downward cost [EU/MWh]
fsp0	572	load	0.53158			39.76	39.52			1.99	1.98
fsp1	775	load	1.16947			39.61	39.31			1.98	1.97
fsp2	1163	load	0.00726	5.00%		39.73	39.8			1.99	1.99
fsp3	1167	load	0.00726		5.00%	39.82	39.79	5.00%	5.00%	1.99	1.99
fsp4	1173	load	0.00726			39.16	40.01			1.96	2.00
fsp5	1163	gen	0.0015	0.00%		39.89	39.58			1.99	1.98
fsp6	829	load	0.00363	5.00%		39.51	39.78			1.98	1.99

fsp7	829	gen	0.0015	0.00%		39.81	39.24			1.99	1.96
fsp8	829	stor	0.003			39.69	40			1.98	2.00
fsp9	1142	load	0.00605			39.75	40.23			1.99	2.01
fsp10	1142	gen	0.0015	0.00%		39.73	39.35			1.99	1.97
fsp11	1142	stor	0.003			39.42	39.72			1.97	1.99
fsp12	1181	load	0.00363			40.28	39.82			2.01	1.99
fsp13	1229	load	0.00726			39.42	39.97			1.97	2.00
fsp14	1254	load	0.00726			40.04	39.75			2.00	1.99
fsp15	1264	load	0.00605			39.81	39.68			1.99	1.98
fsp16	1274	load	0.00726			39.87	39.73			1.99	1.99
fsp17	1276	load	0.00726			39.35	39.94			1.97	2.00
fsp18	1285	load	0.00363			40.12	39.63			2.01	1.98
fsp19	1285	gen	0.0015	0.00%		39.61	40.09			1.98	2.00
fsp20	1285	stor	0.003	5.00%		39.45	39.6			1.97	1.98
fsp21	1362	load	0.00726			39.62	39.92			1.98	2.00
fsp22	1362	gen	0.0015	0.00%		39.83	39.66			1.99	1.98
fsp23	1362	stor	0.003	5.00%		39.44	39.88			1.97	1.99

2.4.1.2 Step 2: SRA scenarios

Different scenarios are tested for the quantitative SRA of the PT-NET1-MV-LV demo site according to Table 2.35. This table also summarizes the SRA parameters and the KPIs to be calculated for each scenario. Two scenarios are defined. First, we analyzed the PT-NET1-MV-LV network considering the load and generation annual profiles described in the previous subsection (Scenario 0), resulting in no congested elements. Second, Scenario 1 examines the congestion events in the network under the conditions of Scenario 0, but the consumption of a MV load client connected to bus 585 was increased by 1 MW. This load point was selected after a power flow analysis where the area with more lines close to being congested was identified. The quantitative SRA methodology is applied for each of these scenarios, and the results are further analyzed in the following subsections.

Table 2.35 SRA scenarios for the Portuguese network

Scenario ID	Description	SRA parameters	KPIs
Scenario 0	Initial yearly profiles	No congested elements	
Scenario 1	Increasing load in a MV client, installation of an extra 1 MW in bus 585.	Load scaling up, FSPs bid size, Bus voltage limits	EU_KPI_1: Increased RES and DER hosting capacity EU_KPI_2: Increase of energy storage solutions penetration CM_KPI_4: Avoided restrictions PT_KPI_03: Avoided CO2 emissions from increased hosting capacity

2.4.1.3 Step 3: LFM model

a) SRA Scenario 0

The SRA methodology described in Subchapter 2.1 is applied for Scenario 0 of PT-NET1-MV-LV. Therefore, this section describes the results of the required steps considered for this methodology:

- **Flexibility needs calculation (Step 3.1):** The first step is to perform a power flow analysis for 8760 hours (market horizon) to identify possible constraints in the grid. This analysis considers network data, and load and generation initial profiles described in previous subsections. Figure 2.53, Figure 2.54, and Figure 2.55 present the results for the Scenario 0 conditions. These results show that congestion events (lines and transformers overloading) do not occur under this scenario. By contrast, as shown in Figure 2.55, the voltage magnitude of some buses is less than 0.95 p.u in January and December. It is important to note that these resulting flexibility needs are focused only on voltage control, which is not in line with the overall objective of the BUCs in the Portuguese demonstrator, to test a LFM for both congestion management or voltage control services. Therefore, it becomes necessary to define a new scenario that aligns with this objective, which is analyzed in the following subsection.

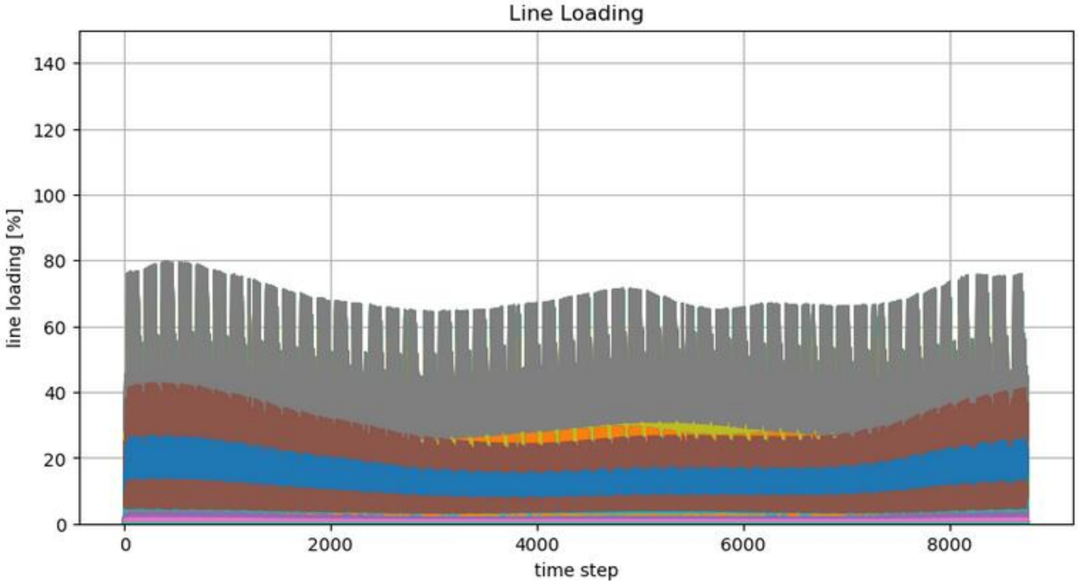


Figure 2.53 Lines loading [%] for the Scenario 0, PT-NET1-MV-LV

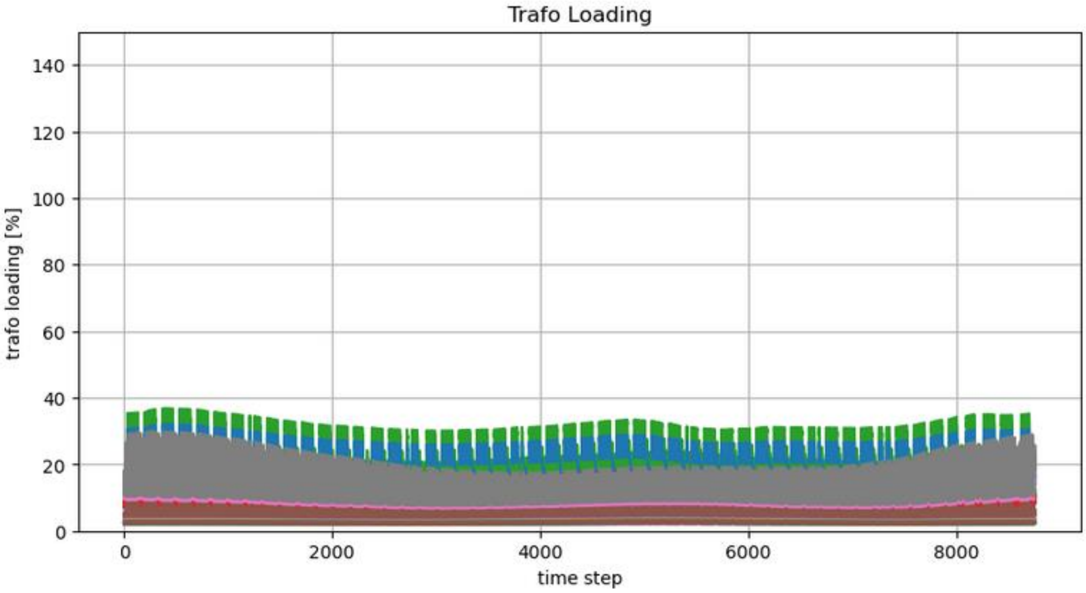


Figure 2.54 Transformers loading [%] for the Scenario 0, PT-NET1-MV-LV

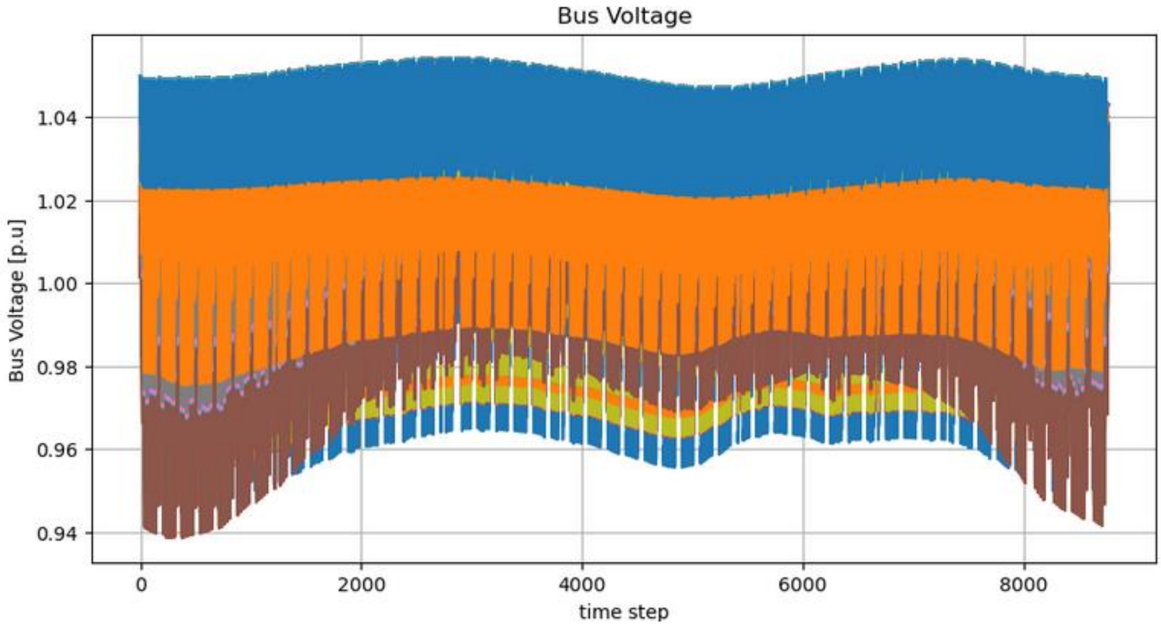


Figure 2.55 Buses Voltage [p.u.] for the Scenario 0, PT-NET1-MV-LV

b) SRA Scenario 1

This section presents the results obtained by applying the quantitative SRA methodology for Scenario 1 of PT-NET1-MV-LV, which was defined in Table 2.35. This scenario examines the congestion events in the network under the conditions of Scenario 0, but the consumption of a MV load client connected to bus 585 was increased by 1 MW. The results are described below for each step of the SRA methodology.

- **Flexibility needs calculation (Step 3.1):** Considering the new load profiles, a power flow analysis is run for 8760 hours to identify potential constraints. Figure 2., Figure 2., and Figure 2. present results for lines loading, transformers loading, and bus voltage magnitude, respectively. From these figures, we identified that some lines are congested and some buses have undervoltage values (below 0.95 p.u.). In this scenario, there are no congestion problems in the transformers. Based on power flow results, the corresponding flexibility needs are computed. Table 2.36 summarizes scenario 1 flexibility needs and network issues associated with congestion management and voltage control, resulting in 354 congestion problems and 571 voltage violations. These values are determined by considering the number of congested elements multiplied by the hours when these problems occur.

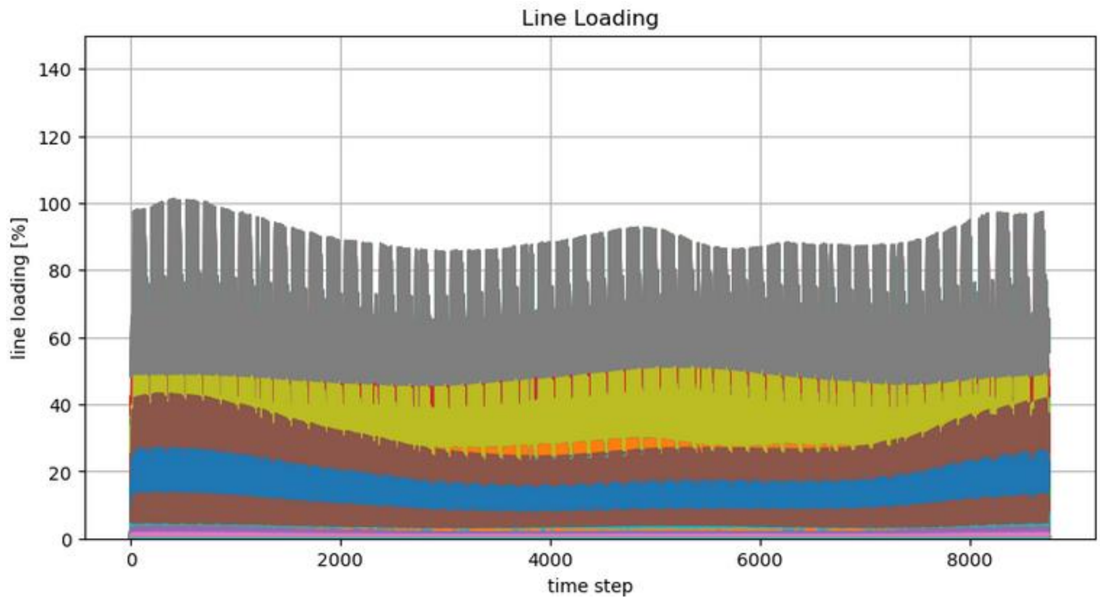


Figure 2.56 Lines loading [%] for the Scenario 1, PT-NET1-MV-LV

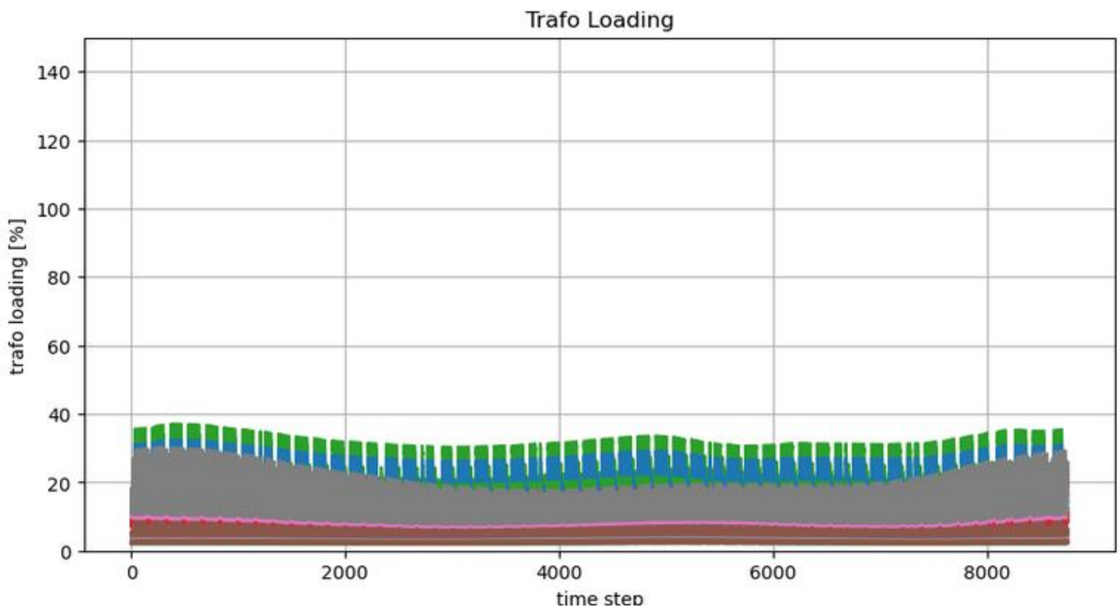


Figure 2.57 Transformer loading [%] for the Scenario 1, PT-NET1-MV-LV

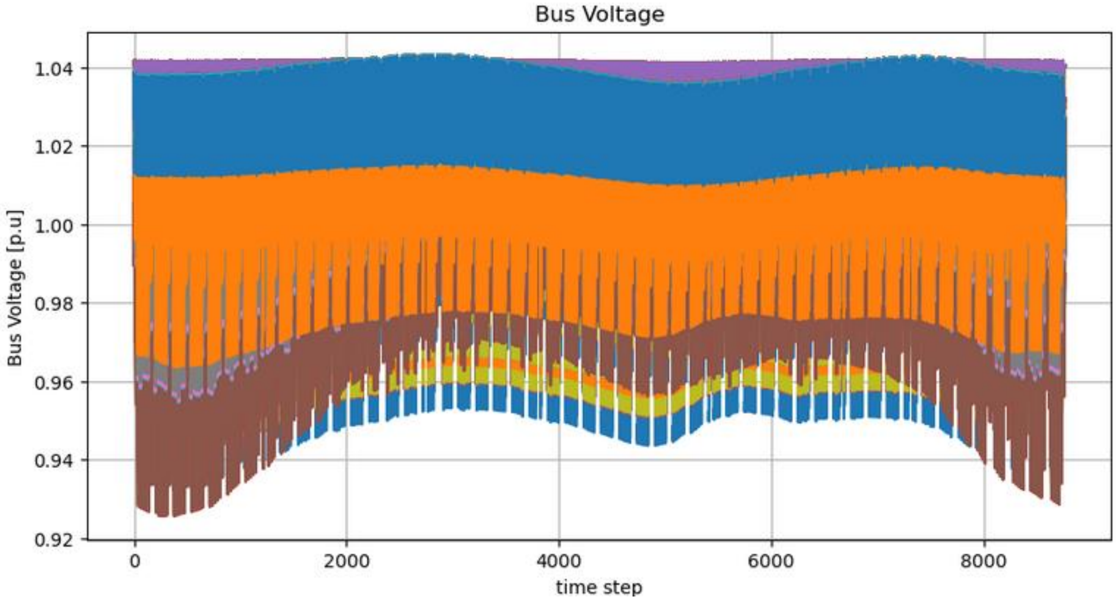


Figure 2.58 Bus Voltage [p.u.] for the Scenario 1, PT-NET1-MV-LV

Table 2.36 Summary of Flexibility Needs for PT-NET1-MV-LV

Congestion management and voltage control flexibility needs	Value
Congested lines and/or transformers	Lines #: 3888, 3952, 4005, 4020, 4061, 4186, 4238, 4425, and 4605
Total congestion problems (congested elements by hours)	354
Overvoltage problems (bus with overvoltage by hours)	0
Undervoltage problems (bus with undervoltage by hours)	571

- **Sensitivity factors calculation (Step 3.2):** In this step, sensitivity factors are computed for each FSP participating in the local market relative to the flexibility needs obtained in the previous step. As stated in Section 2.1, sensitivity factors for congestion management describe how the apparent power of a congested line or transformer could be impacted by variations in the active (dS/dP) or reactive (dS/dQ) power provided by FSPs. For voltage control, sensitivity factors indicate how the voltage at a specific node could be impacted by variations in active (dV/dP) or reactive (dV/dQ) power provided by the FSP. Although sensitivity factors could be calculated for each hour of study depending on the operation point of the network, in the SRA they have been computed for the worst hour of study (hour with the maximum line/trafo overloading for congestion management, hour with the maximum deviation from bus voltage limits for voltage control).

  Regarding congestion management, Table 2.37 list sensitivity factors (dS/dP) and Table 2.38 shows sensitivity factors (dS/dQ) for all congested lines. The positive sign of the sensitivity factors implies a direct relationship, which means that an increase in P or Q in FSP results in a rise in the S value of the congested element. A negative sign implies an opposite behavior. With regards to voltage control, Table 2.18 provide a summary of computed sensitivity factors for (dV/dP) and (dV/dQ), respectively.

Table 2.37 Sensitivity factors (dS/dP) for congestion management, PT-NET1-MV-LV ([14])

FSP ID	FSP type	Sensitivity factors dS/dP								
		LINE 3888	LINE 3952	LINE 4005	LINE 4020	LINE 4061	LINE 4186	LINE 4238	LINE 4425	LINE 4605
fsp0	load	-1.041	-1.024	-1.029	-1.028	-1.032	-1.045	-1.050	-1.025	-1.022
fsp1	load	-1.038	-1.021	-1.026	-1.024	-1.029	-1.042	-1.046	-1.022	-1.019
fsp2	load	-1.176	-1.156	-1.162	-1.160	-1.165	-1.180	-1.185	-1.157	-1.154
fsp3	load	-1.176	-1.156	-1.162	-1.160	-1.165	-1.180	-1.185	-1.157	-1.154
fsp4	load	-1.176	-1.156	-1.162	-1.160	-1.165	-1.180	-1.185	-1.158	-1.154
fsp5	generator	-1.176	-1.156	-1.162	-1.160	-1.165	-1.180	-1.185	-1.157	-1.154
fsp6	load	-1.097	-1.078	-1.084	-1.082	-1.087	-1.100	-1.105	-1.079	-1.077
fsp7	generator	-1.097	-1.078	-1.084	-1.082	-1.087	-1.100	-1.105	-1.079	-1.077
fsp8	storage	-1.097	-1.078	-1.084	-1.082	-1.087	-1.100	-1.105	-1.079	-1.077
fsp9	load	-1.176	-1.156	-1.162	-1.160	-1.165	-1.180	-1.185	-1.157	-1.154
fsp10	generator	-1.176	-1.156	-1.162	-1.160	-1.165	-1.180	-1.185	-1.157	-1.154
fsp11	storage	-1.176	-1.156	-1.162	-1.160	-1.165	-1.180	-1.185	-1.157	-1.154
fsp12	load	-1.115	-1.096	-1.101	-1.100	-1.104	-1.118	-1.123	-1.097	-1.094
fsp13	load	-1.097	-1.078	-1.084	-1.082	-1.087	-1.101	-1.105	-1.079	-1.077
fsp14	load	-1.110	-1.091	-1.097	-1.095	-1.100	-1.114	-1.119	-1.092	-1.090
fsp15	load	-1.098	-1.079	-1.085	-1.083	-1.088	-1.101	-1.106	-1.080	-1.077
fsp16	load	-1.095	-1.076	-1.082	-1.080	-1.085	-1.098	-1.103	-1.077	-1.074
fsp17	load	-1.100	-1.082	-1.087	-1.086	-1.090	-1.104	-1.109	-1.083	-1.080
fsp18	load	-1.123	-1.104	-1.110	-1.108	-1.113	-1.127	-1.132	-1.105	-1.102
fsp19	generator	-1.123	-1.104	-1.110	-1.108	-1.113	-1.127	-1.132	-1.105	-1.102
fsp20	storage	-1.123	-1.104	-1.110	-1.108	-1.113	-1.127	-1.132	-1.105	-1.102
fsp21	load	-1.096	-1.077	-1.083	-1.081	-1.086	-1.099	-1.104	-1.078	-1.075
fsp22	generator	-1.096	-1.077	-1.083	-1.081	-1.086	-1.099	-1.104	-1.078	-1.075
fsp23	storage	-1.096	-1.077	-1.083	-1.081	-1.086	-1.099	-1.104	-1.078	-1.075

[14] Sensitivity factors have been computed for the worst hour of study, in this case, hour 419.

Table 2.38 Sensitivity factors (dS/dQ) for congestion management, PT-NET1-MV-LV ([15])

FSP ID	FSP type	Sensitivity factors dS/dQ								
		LINE 3888	LINE 3952	LINE 4005	LINE 4020	LINE 4061	LINE 4186	LINE 4238	LINE 4425	LINE 4605
fsp0	load	-0.356	-0.348	-0.350	-0.350	-0.352	-0.358	-0.360	-0.349	-0.347
fsp1	load	-0.355	-0.347	-0.349	-0.349	-0.351	-0.357	-0.359	-0.347	-0.346
fsp2	load	-0.395	-0.386	-0.389	-0.388	-0.390	-0.397	-0.400	-0.387	-0.385
fsp3	load	-0.395	-0.386	-0.389	-0.388	-0.391	-0.397	-0.400	-0.387	-0.385
fsp4	load	-0.395	-0.386	-0.389	-0.388	-0.390	-0.397	-0.400	-0.387	-0.385
fsp5	generator	-0.395	-0.386	-0.389	-0.388	-0.390	-0.397	-0.400	-0.387	-0.385
fsp6	load	-0.374	-0.366	-0.368	-0.368	-0.370	-0.376	-0.379	-0.366	-0.365
fsp7	generator	-0.374	-0.366	-0.368	-0.368	-0.370	-0.376	-0.379	-0.366	-0.365
fsp8	storage	-0.374	-0.366	-0.368	-0.368	-0.370	-0.376	-0.379	-0.366	-0.365
fsp9	load	-0.395	-0.386	-0.389	-0.388	-0.390	-0.397	-0.400	-0.387	-0.385
fsp10	generator	-0.395	-0.386	-0.389	-0.388	-0.390	-0.397	-0.400	-0.387	-0.385
fsp11	storage	-0.395	-0.386	-0.389	-0.388	-0.390	-0.397	-0.400	-0.387	-0.385
fsp12	load	-0.380	-0.371	-0.374	-0.373	-0.376	-0.382	-0.385	-0.372	-0.371
fsp13	load	-0.375	-0.366	-0.368	-0.368	-0.370	-0.376	-0.379	-0.367	-0.365
fsp14	load	-0.379	-0.370	-0.373	-0.372	-0.374	-0.381	-0.383	-0.371	-0.369
fsp15	load	-0.375	-0.366	-0.369	-0.368	-0.370	-0.377	-0.379	-0.367	-0.365
fsp16	load	-0.374	-0.365	-0.368	-0.367	-0.369	-0.376	-0.378	-0.366	-0.365
fsp17	load	-0.375	-0.367	-0.369	-0.369	-0.371	-0.377	-0.380	-0.367	-0.366
fsp18	load	-0.383	-0.374	-0.376	-0.376	-0.378	-0.384	-0.387	-0.374	-0.373
fsp19	generator	-0.383	-0.374	-0.376	-0.376	-0.378	-0.384	-0.387	-0.374	-0.373
fsp20	storage	-0.383	-0.374	-0.376	-0.376	-0.378	-0.384	-0.387	-0.374	-0.373
fsp21	load	-0.373	-0.364	-0.367	-0.366	-0.369	-0.375	-0.377	-0.365	-0.364
fsp22	generator	-0.373	-0.364	-0.367	-0.366	-0.369	-0.375	-0.377	-0.365	-0.364
fsp23	storage	-0.373	-0.364	-0.367	-0.366	-0.369	-0.375	-0.377	-0.365	-0.364

[15] Sensitivity factors have been computed for the worst hour of study, in this case, hour 419.

Table 2.39 Sensitivity factors (dV/dP) for voltage control, PT-NET1-MV-LV ([16])

FSP ID	FSP type	Sensitivity factors dV/dP																					
	Busses:	**572**	**775**	**829**	**859**	**1028**	**1075**	**1103**	**1108**	**1142**	**1157**	**1163**	**1167**	**1173**	**1175**	**1181**	**1229**	**1254**	**1264**	**1274**	**1276**	**1285**	**1362**
fsp0	load	0.029	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp1	load	0.000	0.029	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp2	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.815	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp3	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.822	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp4	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.914	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp5	generator	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.815	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp6	load	0.000	0.000	0.681	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp7	generator	0.000	0.000	0.681	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp8	storage	0.000	0.000	0.681	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp9	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.726	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp10	generator	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.726	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp11	storage	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.726	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp12	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.889	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp13	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.439	0.000	0.000	0.000	0.000	0.000	0.000
fsp14	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.763	0.000	0.000	0.000	0.000	0.000
fsp15	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.528	0.000	0.000	0.000	0.000
fsp16	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.387	0.000	0.000	0.000
fsp17	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.836	0.000	0.000
fsp18	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.511	0.000
fsp19	generator	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.511	0.000
fsp20	storage	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.511	0.000
fsp21	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.000
fsp22	generator	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.000
fsp23	storage	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.000

[16] Sensitivity factors have been computed for the worst hour of study, in this case, hour 283.

Table 2.40 Sensitivity factors (dV/dQ) for voltage control, PT-NET1-MV-LV ([17])

FSP ID	FSP type	Sensitivity factors dV/dQ																					
	Busses:	**572**	**775**	**829**	**859**	**1028**	**1075**	**1103**	**1108**	**1142**	**1157**	**1163**	**1167**	**1173**	**1175**	**1181**	**1229**	**1254**	**1264**	**1274**	**1276**	**1285**	**1362**
fsp0	load	0.026	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp1	load	0.000	0.027	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp2	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.931	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp3	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.935	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp4	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	7.037	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp5	generator	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.931	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp6	load	0.000	0.000	0.675	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp7	generator	0.000	0.000	0.675	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp8	storage	0.000	0.000	0.675	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp9	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.836	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp10	generator	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.836	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp11	storage	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	6.836	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp12	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.875	0.000	0.000	0.000	0.000	0.000	0.000	0.000
fsp13	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.433	0.000	0.000	0.000	0.000	0.000	0.000
fsp14	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.751	0.000	0.000	0.000	0.000	0.000
fsp15	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.521	0.000	0.000	0.000	0.000
fsp16	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.382	0.000	0.000	0.000
fsp17	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.828	0.000	0.000
fsp18	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.500	0.000
fsp19	generator	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.500	0.000
fsp20	storage	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.500	0.000
fsp21	load	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.023
fsp22	generator	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.023
fsp23	storage	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.023

[17] Sensitivity factors have been computed for the worst hour of study, in this case, hour 283.

- **FSP's bid generation (Step 3.3):** This step computes the flexibility limit that each FSP can provide, both downward and upward, for active and reactive power, based on FSPs characteristics provided in Table 2.34.
- **Local flexibility market-clearing (Step 3.4) and post-evaluation (Step 3.5):** In step 3.4, a local flexibility market-clearing is carried out to solve the criticalities identified in step 3.1 using the most efficient flexibility bids from FSPs (step 3.3) at minimum cost. The LFM clearing considers the sensitivities factors computed in step 3.2 as a representation of the network constraints.

To evaluate the SRA performance of scenario 1, sensitivities are applied to three key SRA parameters presented in Table 2.41. The first parameter involves modifying the bus voltage limits considered in the model. The second parameter entails increasing the upwards and downwards flexibility capacity of the FSPs. Lastly, changes in the storage capacity of FSP5 were considered as the third parameter. Furthermore, it should be emphasized that a cost of 5890 (EUR/MWh) is considered for the VOLL parameter in the Portuguese demonstrator according to the report in [19].

Table 2.41 Sensitivities to the SRA parameters for scalability, Scenario 1, PT-NET1-MV-LV

Parameter	Parameter description	Sensitivity Range
M02, M03	Limits of maximum and minimum permissible voltage levels for buses	$M0x = [v_{min}, v_{max}]$ $M02 = [0.93, 1.07]$ $M03 = [0.90, 1.10]$
F01, F03, F05	Increase in available flexibility from FSPs	*F0x* = [5%, 15%, 25%]
SK01	Increase in storage capacity of FSP 5.	*SK0x* = [Nominal Capacity]

Table 2.42 and Table 2.43 summarize the results obtained after the market clearing for each scenario that has been evaluated considering the SRA sensitivities of this demo site. In both tables, the cost of the Objective Function equals the sum of the costs of the total active and reactive power FSP's bids cleared in the market plus the cost of the auxiliary variables Alpha and Beta, which implies that the model has been satisfactorily solved. Alpha represents the cost of the flexibility not supplied by the Voltage Control component while Beta corresponds to the cost of the flexibility not supplied by the Congestion Management component[18]. As the capacities of the FSPs increase (from F01 to F05), the associated costs of Alpha and Beta decrease. Given the high costs attributed to these factors, their reduction aligns with the model's objective to minimize total costs. Furthermore, it can be noted that under conditions with lower voltage boundary constraints (specifically M03 in comparison to M02), the cost of Alpha becomes zero.

Additionally, Table 2.44*Table 2.22* presents SRA results obtained by considering a LFM model for both Congestion Management and Voltage Control, where active and reactive power are simultaneously taken into account. It can be seen that this model achieves a greater reduction in total costs compared to the two previous cases, potentially due to a lower unsupplied flexibility.

[18] A comprehensive description of Alpha and Beta can be found in the LFM formulation of Annex II.

Table 2.42 Summary of costs resulting from the market clearing for congestion management and voltage control with active power, Scenario 1, PT-NET1-MV-LV

Scenario	Objective Value [EUR]	Beta Cost [EUR]	Alpha Cost [EUR]	Total Active Power [MW]	Active Power Cost [EUR]	Total Reactive Power [MVAR]	Reactive Power Cost [EUR]
CMVCP_S01_M02_F01_SK01	63232.9	59114.5	4048.6	1.7	68.7	-	-
CMVCP_S01_M02_F03_SK01	3990.7	0.0	3874.1	2.9	114.7	-	-
CMVCP_S01_M02_F05_SK01	3832.6	0.0	3715.1	2.9	115.6	-	-
CMVCP_S01_M03_F01_SK01	59183.7	59114.5	0.0	1.7	68.1	-	-
CMVCP_S01_M03_F03_SK01	114.9	0.0	0.0	2.9	113.1	-	-
CMVCP_S01_M03_F05_SK01	114.8	0.0	0.0	2.9	113.0	-	-

Table 2.43 Summary of costs resulting from the market clearing for congestion Management and voltage control with reactive power, Scenario 1, PT-NET1-MV-LV

Scenario	Objective Value [EUR]	Beta Cost [EUR]	Alpha Cost [EUR]	Total Active Power [MW]	Active Power Cost [EUR]	Total Reactive Power [MVAR]	Reactive Power Cost [EUR]
CMVCQ_S01_M02_F01_SK01	152378.3	148480.6	3897.49	-	-	0.11	0.22
CMVCQ_S01_M02_F03_SK01	150968.8	147145.1	3823.35	-	-	0.19	0.38
CMVCQ_S01_M02_F05_SK01	149761.6	145973.1	3788.03	-	-	0.26	0.51
CMVCQ_S01_M03_F01_SK01	148480.8	148480.6	-	-	-	0.07	0.14
CMVCQ_S01_M03_F03_SK01	147145.4	147145.1	-	-	-	0.14	0.28
CMVCQ_S01_M03_F05_SK01	145973.5	145973.1	-	-	-	0.2	0.4

Table 2.44 Summary of resulting costs from the market clearing for congestion management and voltage control with active and reactive power, Scenario 1, PT-NET1-MV-LV

Scenario	Objective Value [EUR]	Beta Cost [EUR]	Alpha Cost [EUR]	Total Active Power [MW]	Active Power Cost [EUR]	Total Reactive Power [MVAR]	Reactive Power Cost [EUR]
CMVCPQ_S01_M02_F01_SK01	55611.9	51761.3	3783.5	1.7	65.8	0.7	1.3
CMVCPQ_S01_M02_F03_SK01	3674.1	-	3571.1	2.6	101.1	1.0	2.0
CMVCPQ_S01_M02_F05_SK01	3535.1	-	3432.3	2.5	100.6	1.1	2.2
CMVCPQ_S01_M03_F01_SK01	51827.7	51761.3	-	1.7	65.3	0.6	1.2
CMVCPQ_S01_M03_F03_SK01	101.8	-	-	2.5	99.9	1.0	1.9
CMVCPQ_S01_M03_F05_SK01	101.0	-	-	2.5	99.0	1.0	2.0

As technical results, Figure 2.59, Figure 2.60, and Figure 2.61 show deviation plots of all bus voltages [p.u.], before (pre) and after (post) the market, for CMCVP, CMCVQ, and CMCVPQ, across each considered scenario. Moreover, the bar plots accompanying the density plots demonstrate the changes in voltage violations for each scenario. Similarly, Figure 2.62, Figure 2.63, and Figure 2.64 present deviation plots illustrating the load percentage of lines, while the corresponding bar graphs specifically highlight the lines experiencing congestion problems.

From the voltage density plots, it can be seen that as the size of the FSPs increase (from F01 to F05), bus voltages tend to converge within the voltage limits compared to the pre-market conditions. The bar plots show that in M02 cases, the overvoltage problems that were present before the market significantly decrease, while the undervoltage problems are effectively compensated through market mechanisms. Comparing the impacts of CMVCP, CMVCQ, and CMVCPQ model markets, for M02, it can be observed that the latter achieves a remarkable reduction in overvoltage problems as FSPs size increase. In the case of scenario M02, the market successfully resolves voltage problems across various sensitivities of F0x. The market mechanisms prove effective in addressing voltage concerns under different conditions.

Similar behavior can be observed in the graphs depicting the lines, where the occurrence plot moves closer to the maximum thermal limit as the size of the FSPs increase. Notably, the CMVCPQ market model consistently achieves better results compared to CMVCP and CMVCQ in terms of congestion management. Interestingly, when considering only the use of reactive power for congestion management, increasing the capacity of FSPs to provide reactive power does not seem to effectively solve congestion problems. In fact, congestion issues may even intensify. This suggests that the utilization of reactive power alone may not be sufficient to mitigate congestion effectively.

(a) (b)

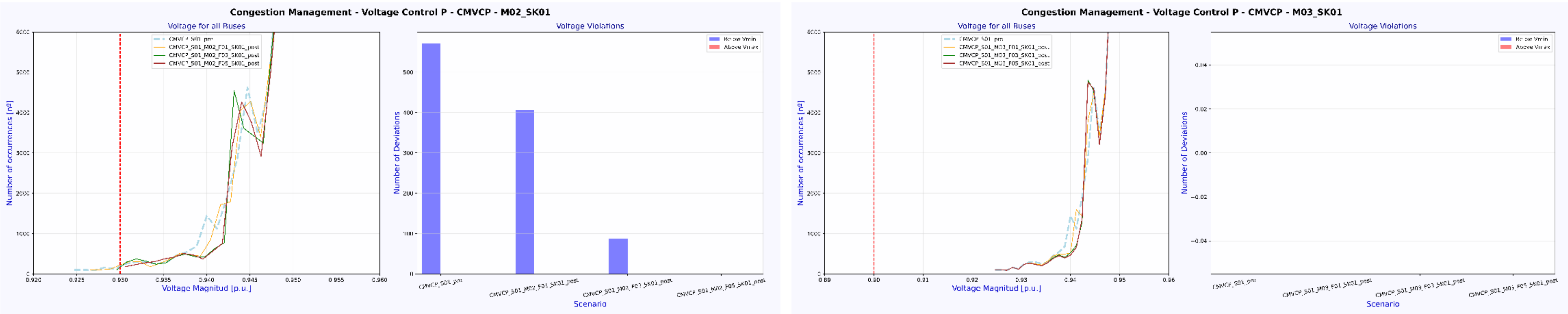


Figure 2.59 Deviation plots for Voltage Magnitude [p.u.] obtained from Congestion Management – Voltage Control with Active Power (a) Scenario M02-SK01, (b) Scenario M03-SK01. Scenario 1, PT-NET1-MV-LV

(a) (b)

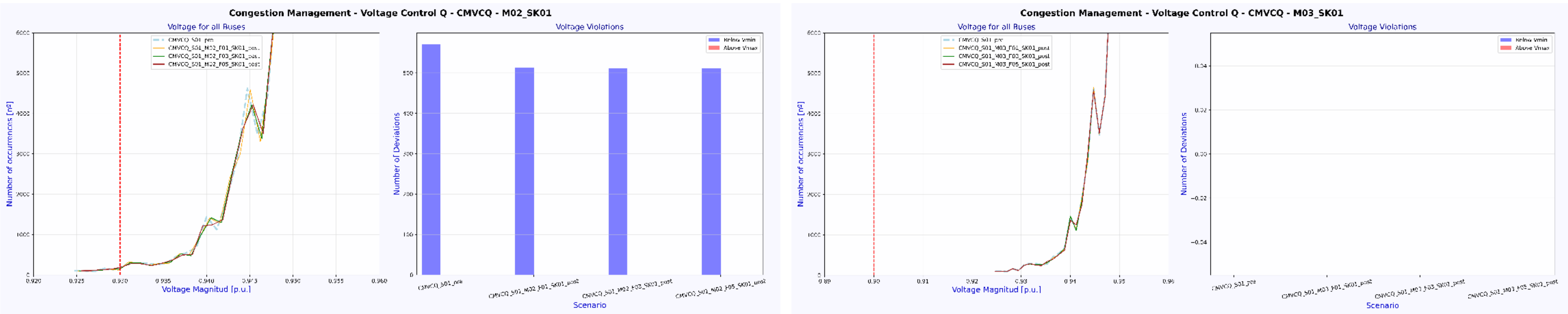
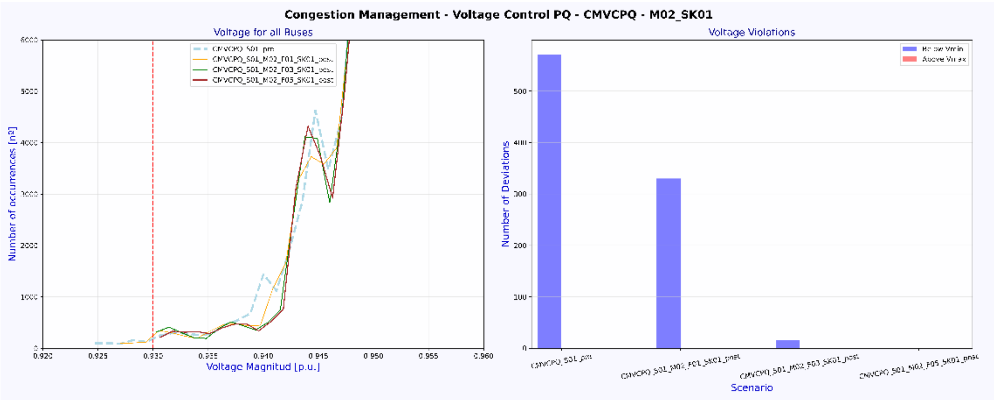


Figure 2.60 Deviation plots for Voltage Magnitude [p.u.] obtained from Congestion Management – Voltage Control with Reactive Power (a) Scenario M02-SK01, (b) Scenario M03-SK01. Scenario 1, PT-NET1-MV-LV

(a)



(b)

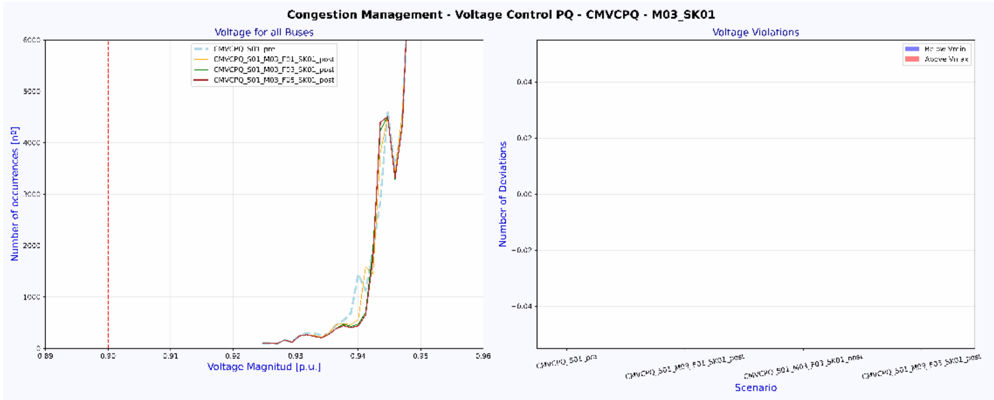
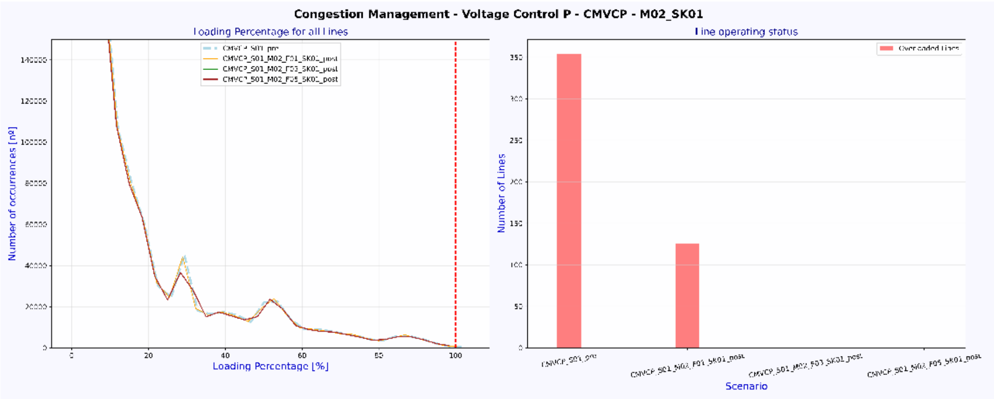


Figure 2.61 Deviation plots for Voltage Magnitude [p.u.] obtained from Congestion Management – Voltage Control with Active and Reactive Power (a) Scenario M02-SK01, (b) Scenario M03-SK01. Scenario 1, PT-NET1-MV-LV

(a)



(b)

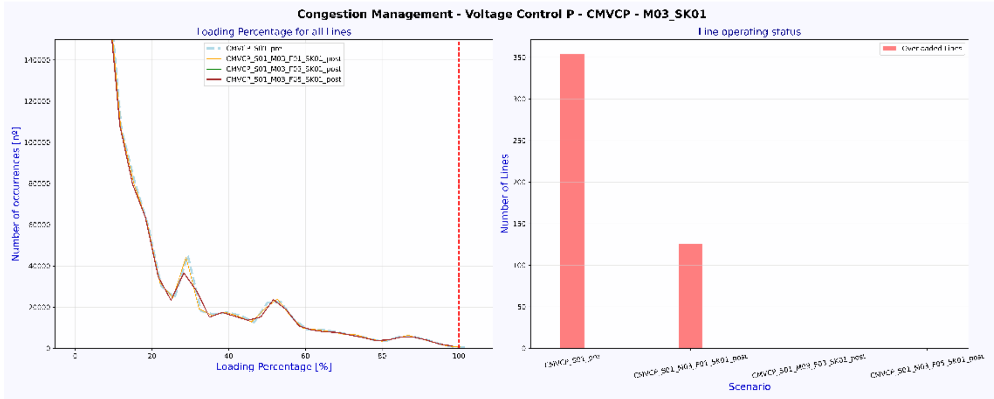
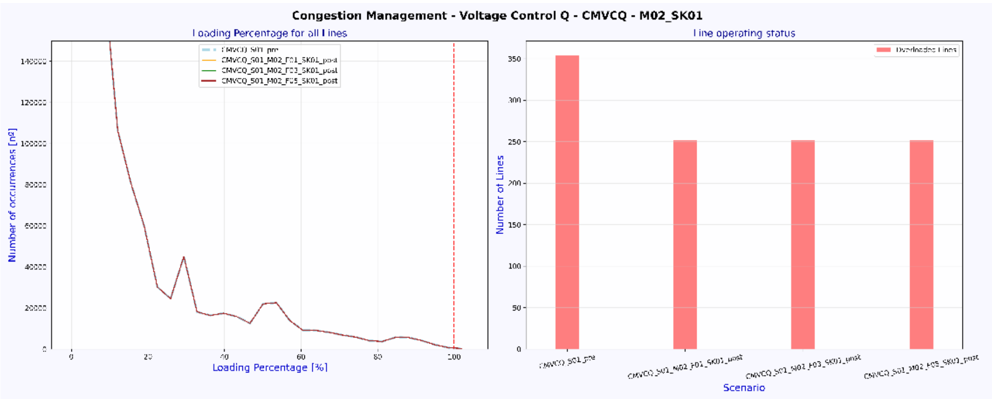


Figure 2.62 Deviation plots for Loading Percentage [%] of all lines obtained from Congestion Management – Voltage Control with Active Power (a) Scenario M02-SK01, (b) Scenario M03-SK01. Scenario 1, PT-NET1-MV-LV

(a)



(b)

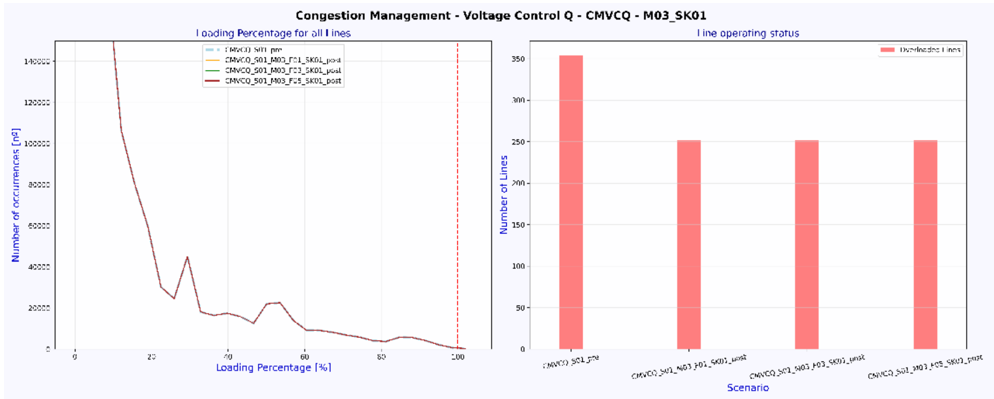
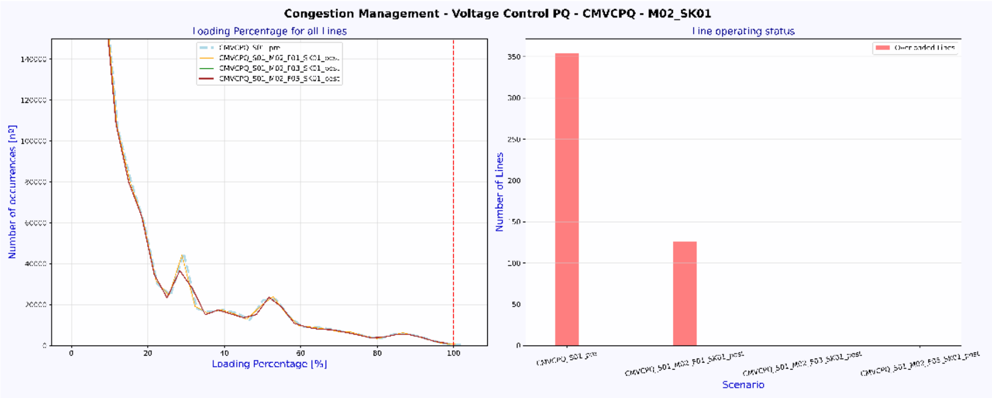


Figure 2.63 Deviation plots for Loading Percentage [%] of all lines obtained from Congestion Management – Voltage Control with Reactive Power (a) Scenario M02-SK01, (b) Scenario M03-SK01. Scenario 1, PT-NET1-MV-LV

(a)



(b)

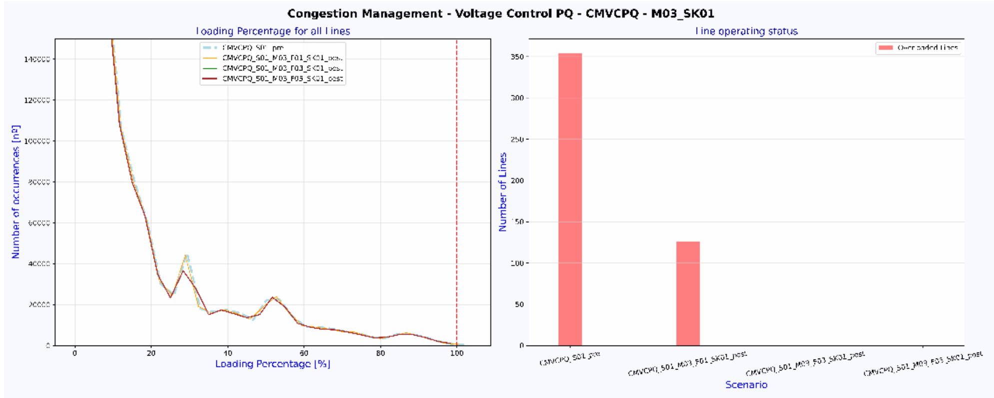


Figure 2.64 Deviation plots for Loading Percentage [%] of all lines obtained from Congestion Management – Voltage Control with Active and Reactive Power (a) Scenario M02-SK02, (b) Scenario M03-SK03. Scenario 1, PT-NET1-MV-LV

2.4.1.4 Step 4: KPIs calculation

2.4.1.4.1 CM_KPI_4: Avoided Restrictions

This KPI quantifies the number of criticalities, such as line or transformer congestion and bus voltage violations that the market models have resolved. Figure 2.65 and Figure 2.66 display the results of all scenarios for CMVCP and CMVCQ, respectively, and considering the sensitivities specified in Table 2.41. Figure 2.67 serves as a comparative analysis, examining how the market dynamics are modified when active and reactive power are used simultaneously in the CMVCPQ market model. The different scenarios are plotted along the horizontal axis, while the vertical axes display, on the left side, the number of restrictions avoided in each component (Nodes, Lines, and Transformers), and on the right side, the Violation Frequency Reduction of the LFM (VFR_LFM) presented as a percentage (red dots).

Finally, it is important to note that other market models have been considered to analyze their impact on the grid. Figure 2.68 depicts the results obtained for this KPI when using only Congestion Management (CM) or Voltage Control (VC).

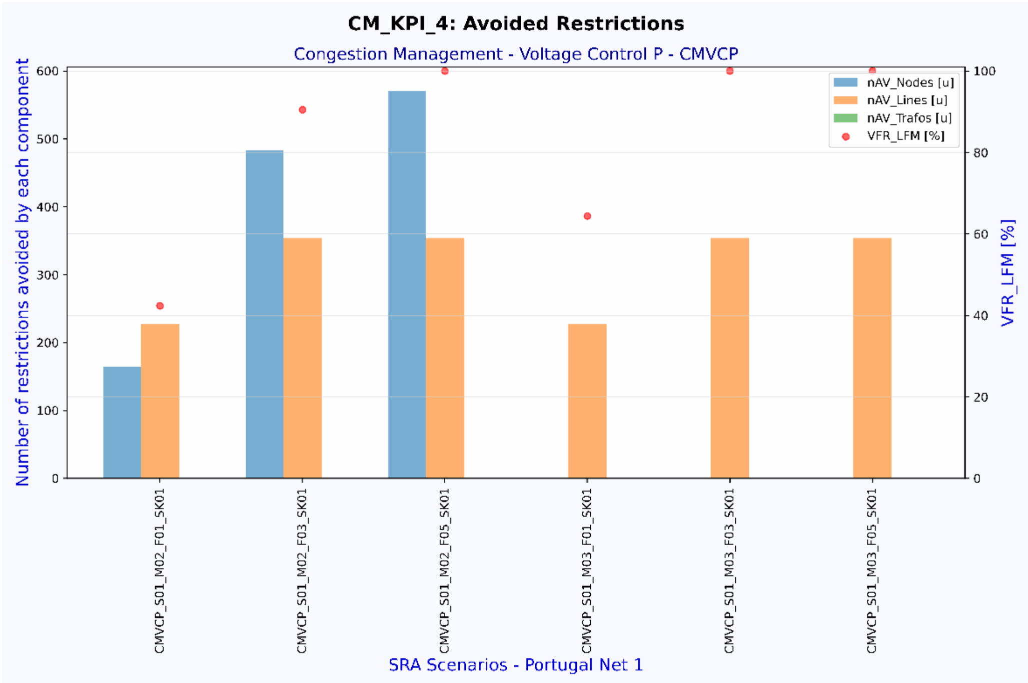


Figure 2.65 KPI CM_SPI_4: Avoided Restrictions, for Congestion Management, Voltage Control using Active Power (CMVCP)

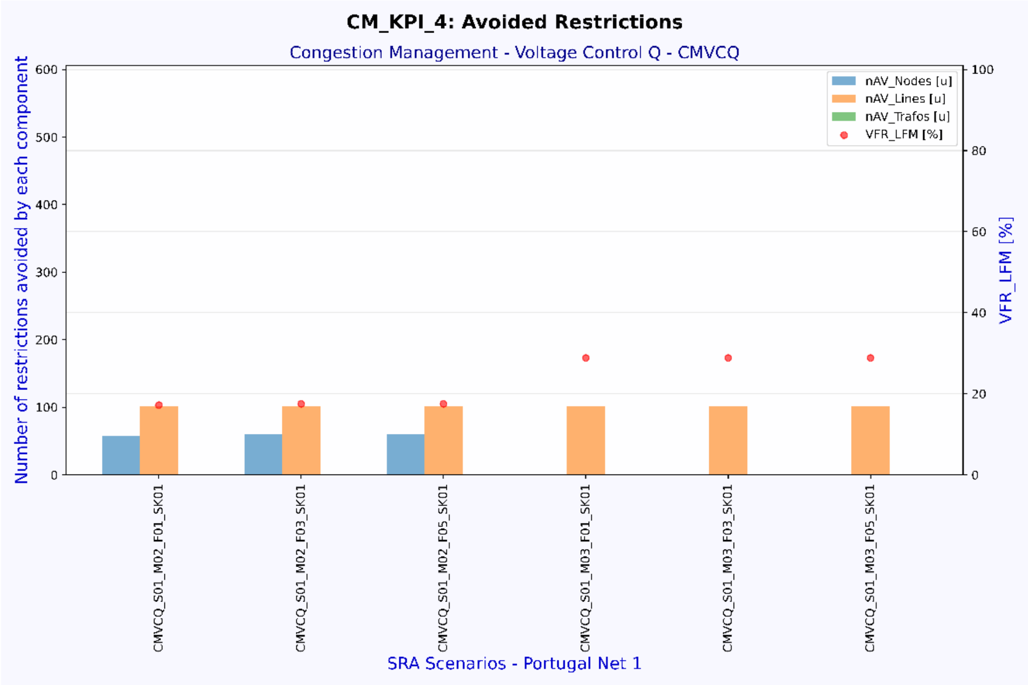


Figure 2.66 KPI CM_SPI_4: Avoided Restrictions, for Congestion Management, Voltage Control using Reactive Power (CMVCQ)

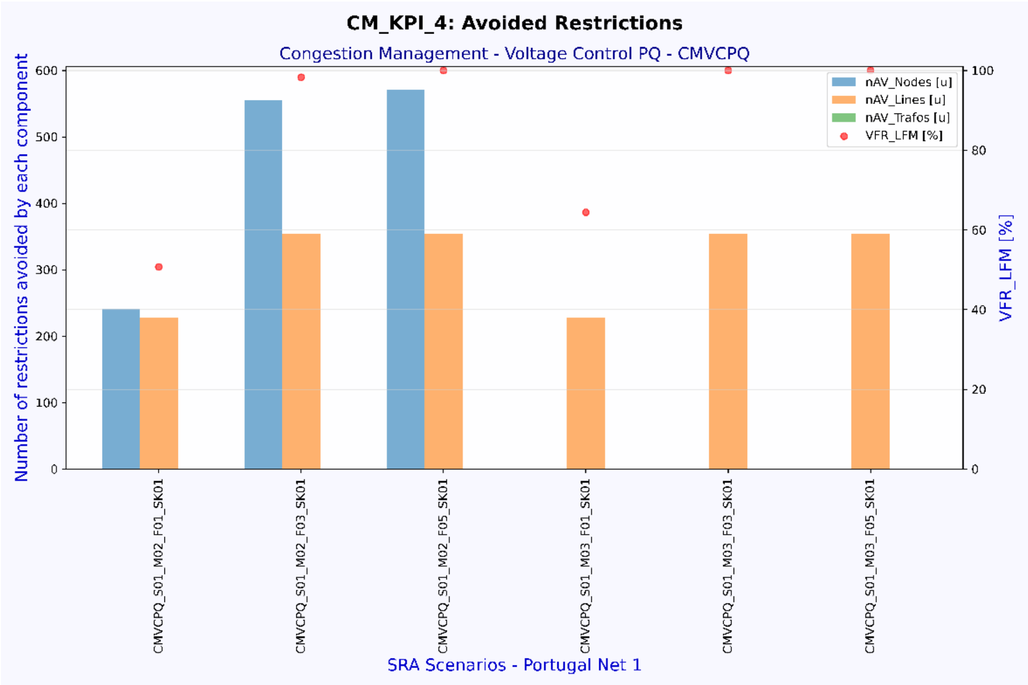
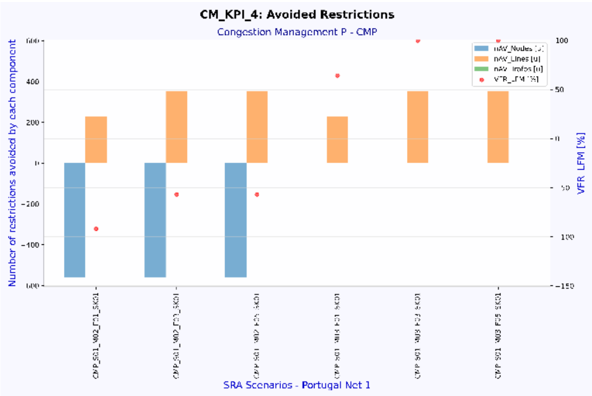
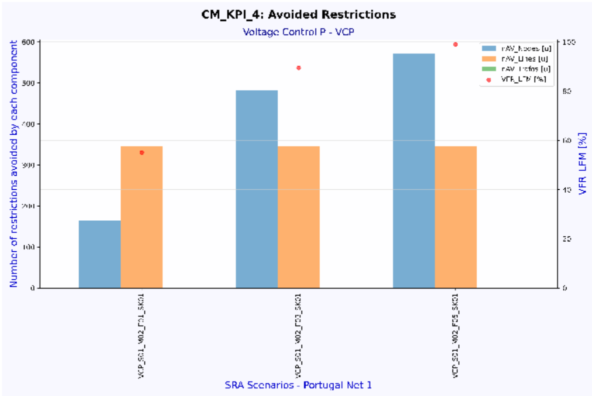


Figure 2.67 KPI CM_SPI_4: Avoided Restrictions, for Congestion Management, Voltage Control using Active or Reactive Power (CMVCPQ)

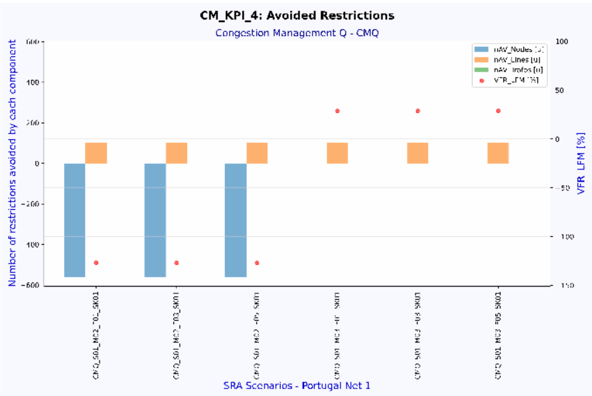
(a1)



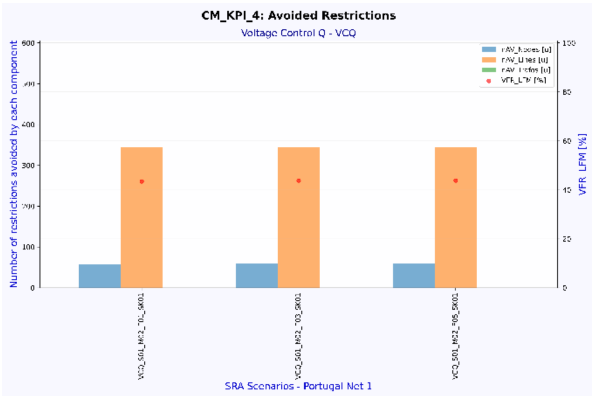
(b1)



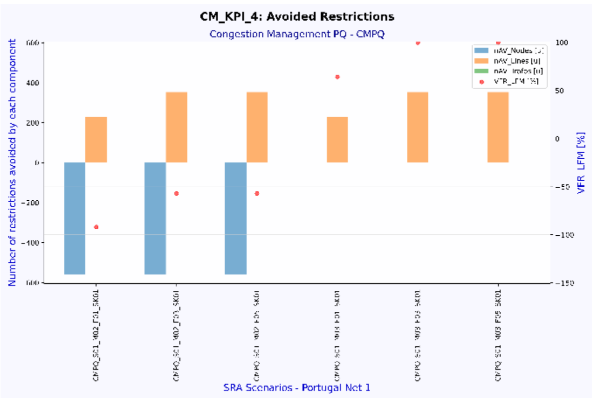
(a2)



(b2)



(a3)



(b3)

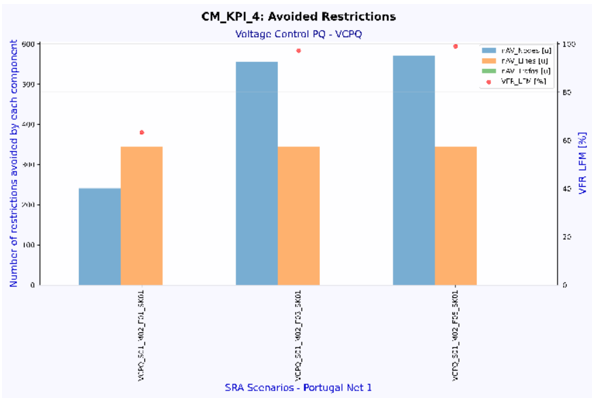


Figure 2.68 CM_KPI_4: Avoided Restrictions:
Congestion Management: a1) Active Power, a2) Reactive Power, a3) Active and Reactive Power.
Voltage Control: b1) Active Power, b2) Reactive Power, b3) Active and Reactive Power

2.4.1.4.2 PT_KPI_3: Avoided CO2 emissions from increased hosting capacity

This KPI quantifies the number of emissions reduced due to the increase in hosting capacity from FSPs. Figure 2.69 and Figure 2.70 display the results of all scenarios for CMVCP and CMVCQ, respectively, and considering the sensitivities specified in Table 2.41. Figure 2.71 serves as a comparative analysis, examining how the market dynamics are modified when active and reactive power are used simultaneously in the CMVCPQ market model. The different scenarios are plotted along the horizontal axis, while the vertical axes display, on the left side, the number of Avoided CO2 emissions.

Finally, it is important to note that other market models have been considered to analyze their impact on the grid. Figure 2.72 depicts the results obtained for this KPI when using only Congestion Management (CM) or Voltage Control (VC).

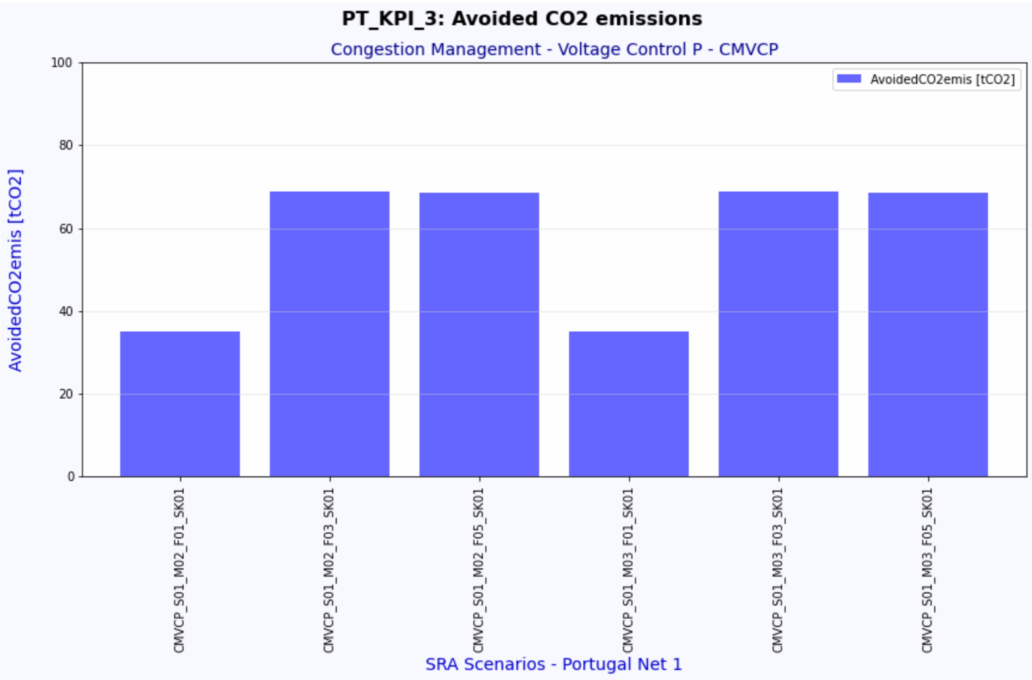


Figure 2.69 PT_KPI_3: Avoided CO2 emissions from increased hosting capacity, for Congestion Management, Voltage Control using Active Power (CMVCP)

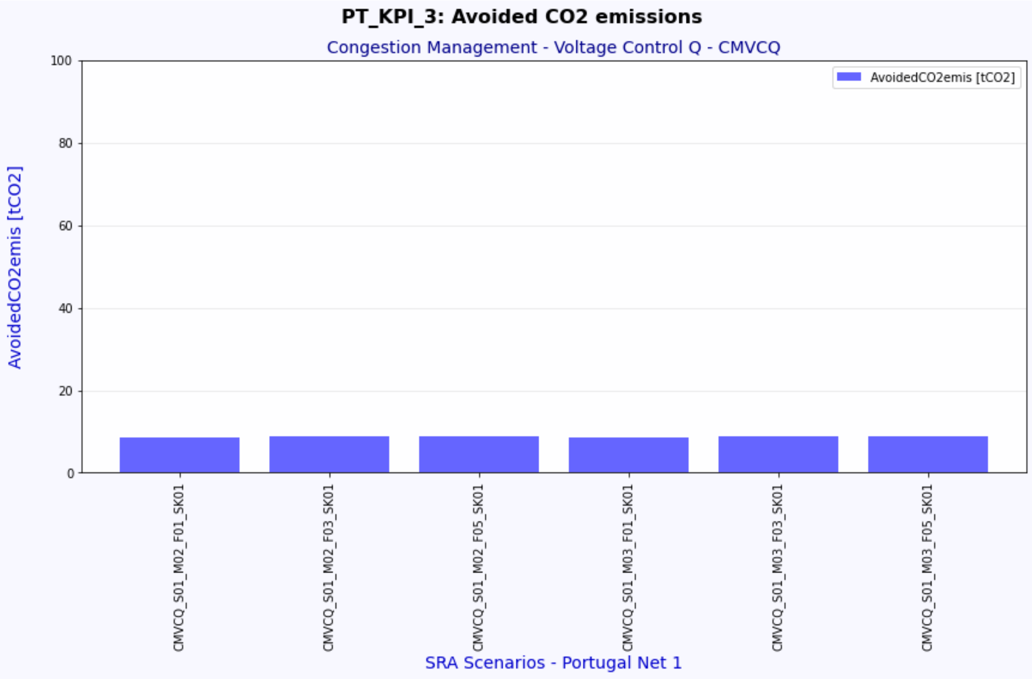


Figure 2.70 PT_KPI_3: Avoided CO2 emissions from increased hosting capacity, for Congestion Management, Voltage Control using Reactive Power (CMVCQ)

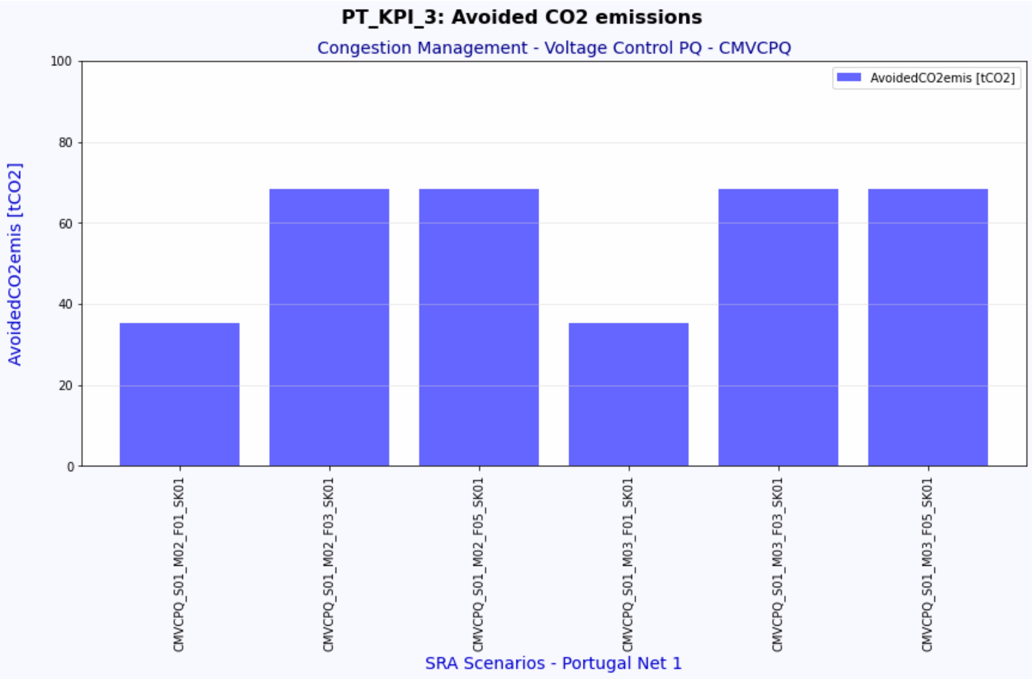


Figure 2.71 PT_KPI_3: Avoided CO2 emissions from increased hosting capacity, for Congestion Management, Voltage Control using Active or Reactive Power (CMVCPQ)

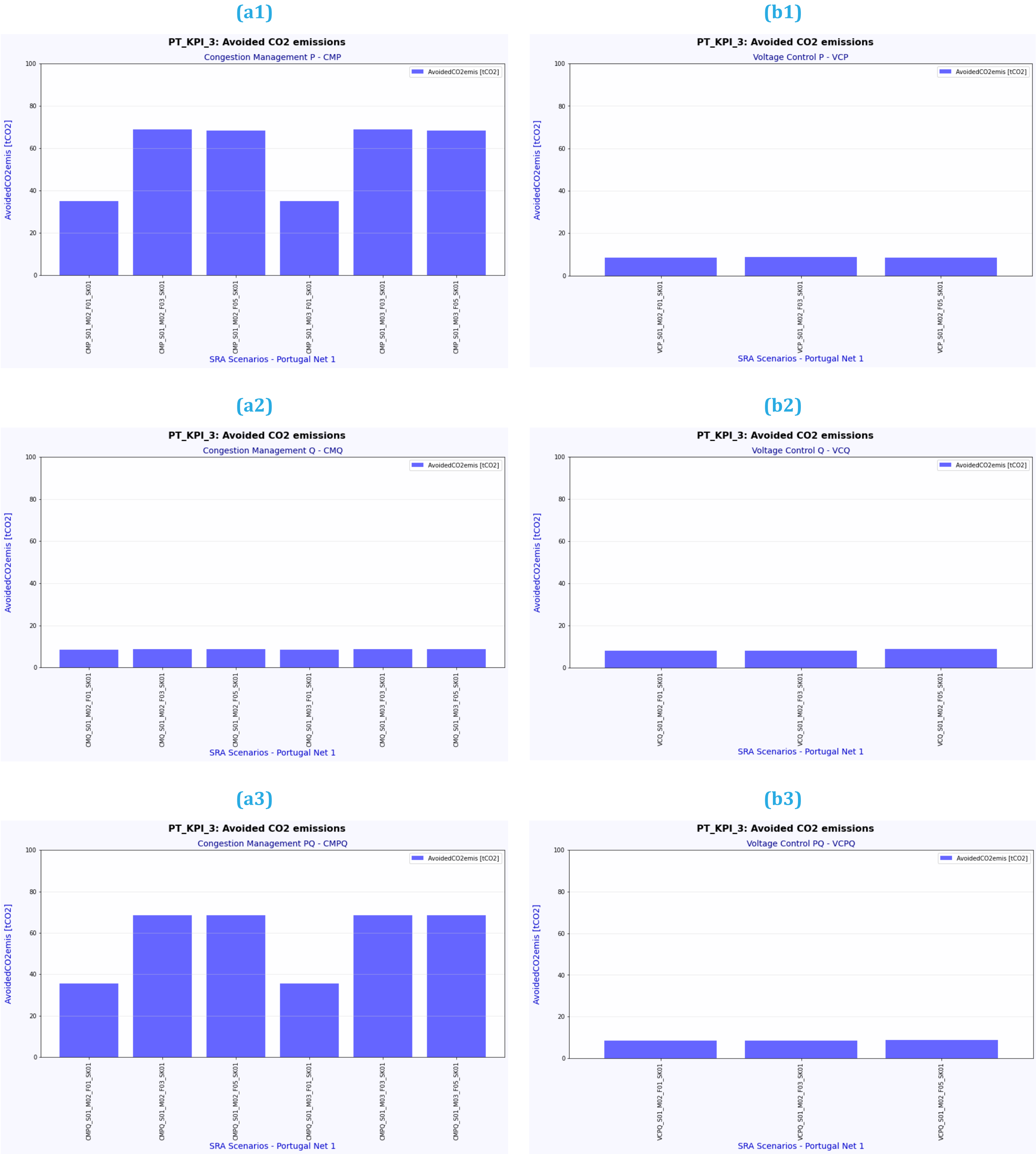


Figure 2.72 PT_KPI_3: Avoided CO2 emissions from increased hosting capacity: Congestion Management: a1) Active Power, a2) Reactive Power, a3) Active and Reactive Power. Voltage Control: b1) Active Power, b2) Reactive Power, b3) Active and Reactive Power

2.4.2 Interim conclusions

For the quantitative SRA of the Portuguese demonstrator two SRA scenarios were tested. Scenario 0 analyzes the PT-NET1-MV-LV network considering initial load and generation profiles resulting in not congestion events. In addition, Scenario 1 examines the congestion events in the network under the conditions of Scenario 0, but the consumption of a MV load client connected to bus 585 was increased by 1 MW. This load point was selected after a power flow analysis where the area with more lines close to being congested was identified. The flexibility needs identified in Scenario 1 involve two main criticalities, i) The overloading of nine lines located in the same MV feeder and ii) Undervoltage problems in a LV feeder. With regards to FSPs, two of them are MV clients located downstream where criticalities i) occur. The rest of the FSPs are located in the LV part of the network. A summary of flexibility needs, FSP's characteristics, and the corresponding sensitivity factors were provided in subsection 2.4.1.3.

Furthermore, the SRA of the Portuguese demonstrator assumes that the reactive power support only comes from the generators and the storage since the loads operating a constant power factor are assumed not to be able to provide reactive power only. Moreover, the simulation of the analyzed scenarios considers a reactive power flexibility cost lower than the active power flexibility cost. In scenario 1, there are no busses in which the voltage magnitude is lower than 0.9; hence, the market is called only for the case in which the voltage magnitude lower threshold is set equal to 0.93 (i.e., M02).

Considering the results obtained from the simulations of the standalone voltage control, using active power as the only product allows for resolving the voltage issues observed in the Portuguese network. However, to solve all undervoltage issues, the flexibility bids of the potential FSPs have to reach 25% bandwidth with respect to the given operating point; hence, loads and storage have to decrease their consumption by a 25%. No upward flexibility is offered by generators fed by renewable sources since they are assumed to be already operating at the maximum power. The simulation results highlight that, for the case studied, a small volume of demand response potentially available (i.e., 5%) does not solve all network issues.

On the other side, if used as a standalone product, the reactive power support available in the network does not contribute to solving all undervoltage issues. Given the characteristics of the FSPs considered for the analyzed scenarios, only generation and storage can contribute by adjusting the power factor considering the apparent power capability limits at the operating point. Nevertheless, also for these resources, the corresponding capability curve limits reactive power support actually available with respect to the bidding percentage assumed; hence, the reactive power support available in the network saturates already when shifting from F01 to F03, limiting the positive impact on undervoltages that power factor correction may have.

The combined use of active and reactive power support for voltage control appears to overperform the case in which only active or reactive power is used. The co-optimization of active and reactive power allows to highly reduce the number of residual undervoltage issues already in the case in which the potential flexibility providers offer the smallest amount of operational flexibility. For example, in the F01 case, the residual undervoltages in the case of co-optimization of active and reactive power drops by about 20% with respect to the case of using active power only. Only a few no severe residual voltage violations are observed for the F02 case.

The co-optimization of active and reactive power allows for unlocking the voltage regulation potential offered by the capability curve of the resources, allowing for an operating point that optimally distributes the power flows across the network, reducing the occurrence and severity of voltage violations.

These technical performances are reflected in the economic outcomes of the system service acquisition. In fact, the co-optimized procurement of active and reactive power allows for achieving an operating point that minimizes the overall procurement costs better than in the cases of disjoint procurement. Furthermore, while guaranteeing the best technical performances, being reactive power support two orders of magnitude cheaper than active power support, the co-optimization of active and reactive power allows the most economical trade-off.

In the case of congestion management standalone addressed, using the active power actions is technically more effective than using the reactive power support. Also, in this case, the reactive power support is provided only by generators and storage since loads are operating with a constant power factor. In the case of active power support only, congestion management actions do not solve all issues if only 5% of the response bandwidth is available. A higher volume of flexibility potentially available is required to reach an operating point free from congested elements. In fact, with a 15% downward flexibility available from the resources, all the congestions are solved. In the case of using reactive power actions only, the flexibility bandwidth available already saturates at 5% of the response bandwidth, highlighting that a larger number of potential providers (i.e., storage and generators) would be available in the network to fulfil the congestion management requirements. Alternatively, loads having the capability of operating a variable power factor can be valuable reactive power support providers. The co-optimization of active and reactive power support for congestion management achieves technical performance comparable with using active power control actions only. Compared to the case of voltage control only, the combined use of active and reactive power is less effective in solving the targeted network operation issues. This behavior is related to the nature of congestions since the reactive power flows are usually a share of the active power flows thanks to the preventive power factor correction measures required as network connection conditions for customers.

The standalone congestion management market is not able to solve any voltage problems; hence, in the case studied, solving congestions in lines or transformers does not significantly contribute to the network voltage control; in the case observed, congestion management cannot be considered as an implicit voltage control action. On the contrary, the simulation results highlight that voltage control actions benefit congestion management. In all the considered cases (i.e., only active power, only reactive power, co-optimization of active and reactive power), the voltage control actions allow for solving almost all congestion management issues. Only a few residual congested elements are observed in the case where the service provider support is at the lowest level (i.e., case F01). Therefore, in the scenarios studied for the Portuguese demonstrator, the voltage control actions are also beneficial for congestion management, acting as an implicit network congestion management measure.

Considering the effects on congestion management, the procurement of active power only is more beneficial than the procurement of only reactive power. Moreover, in the studied scenarios, whatever control action is procured (i.e., active power only, reactive power only, co-optimization of active and reactive power), the technical performances in terms of residual congested elements of the combined congestion management and voltage control are similar to the case in which only congestion management is addressed.

When congestion management and voltage control are jointly addressed, as already observed in the case of standalone voltage control, the active power actions well perform in solving undervoltage limits violations, while reactive power support does not allow significant solving the network operation issues due to the service providers' capability limits considered in this scenario. Furthermore, similarly to the case of standalone voltage control, the co-optimization of active and reactive power support achieves the best technical and economic performances by solving the highest number of voltage issues at the minimum cost. It is worth noting that the voltage control effectiveness of the combined action with congestion management achieves a comparable outcome as the case of standalone voltage control. Therefore, in the Portuguese case, the voltage control and congestion management needs are additive, and the consequent network operation solutions are not conflicting, allowing for an overall reduction of operating costs since the two needs can be solved simultaneously by staking the providers' support.

The results of the simulated scenarios for the Portuguese demonstrator highlight that the joint solution of network congestions and voltage control issues allows for reducing the overall network operation costs by achieving optimal technical performances. In the observed scenarios, active power actions are more effective; however, for an equal footing comparison, a higher reactive power support potential need to be unlocked by considering a large number of potential providers capable of providing reactive power support. Nevertheless, co-optimizing active and reactive power allows achieving the highest technical performances for congestion management and voltage control at the minimum operating costs.

2.5 Project level KPIs outcomes

2.5.1 EU_KPI_1: Increased Hosting Capacity

2.5.1.1 Polish Demonstrator

This KPI measures the increase in Hosting Capacity resulting from the network improvements introduced by the market models in each scenario. Figure 2.73 and Figure 2.74 display the results of all scenarios, for CMVCP and CMVCQ, respectively, and taking into account the sensitivities specified in Table 2.9. Figure 2.75 serves as a comparative analysis, examining how the market dynamics are modified when active and reactive power are used simultaneously in the CMVCPQ market model. The different scenarios are plotted along the horizontal axis, while the vertical axes display, on the left side, the increase of Hosting Capacity in MVA.

In the case of the CMVCP market model results (Figure 2.73), it can be observed that as the sizes of the FSPs increase (F01 to F05), there is an improvement in the KPI throughout M01 and M02. Minor changes occur when there are modifications to the storage capacity SK01 and SK02, for M0. However, it can be observed that in M02, at higher values of F03, the Hosting Capacity increases. This can be attributed to the more flexible voltage limits and the larger sizes of the FSPs.

In the case of the CMVCQ market model results (Figure 2.74), the Hosting Capacity obtained after the market is lower than the initial computed before the market. As indicated previously, it suggests that the utilization of reactive power alone may not be sufficient to mitigate criticalities effectively. On the other hand, the CMVCPQ market model presents a significant improvement in the KPI.

Finally, it is important to note that other market models have been considered to analyze their impact on the network. Figure 2.76 depicts the results obtained for this KPI when using only Congestion Management (CM) or Voltage Control (VC). It is generally observed that each market model has a direct impact on the type of criticality avoided, however, it could affect its counterpart.

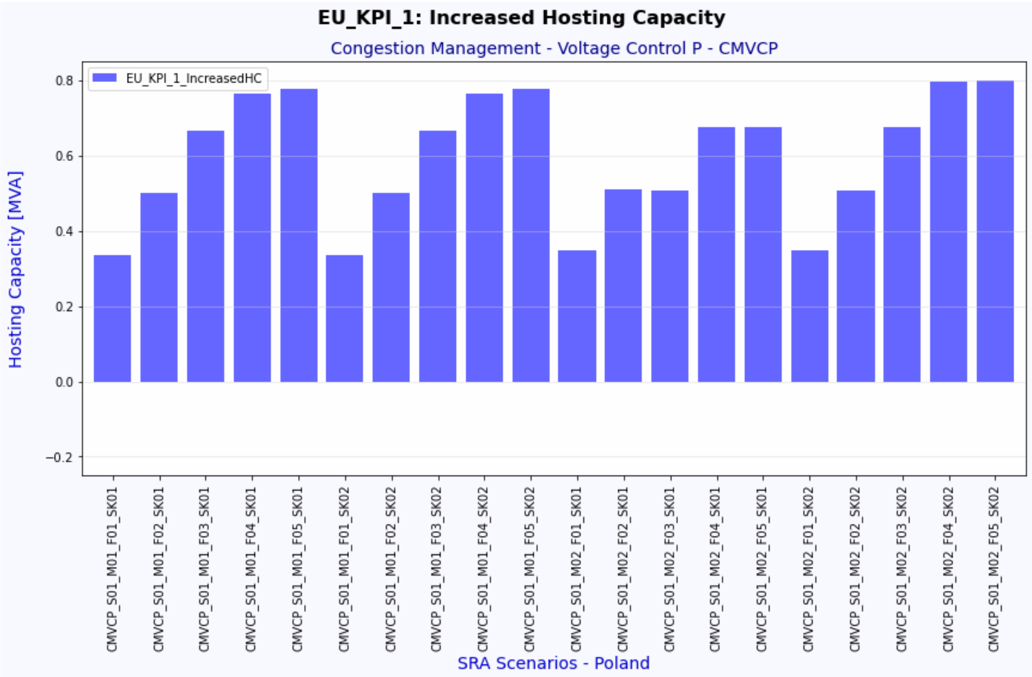


Figure 2.73 EU_KPI_1: Increase Hosting Capacity, for Congestion Management, Voltage Control using Active Power (CMVCP)

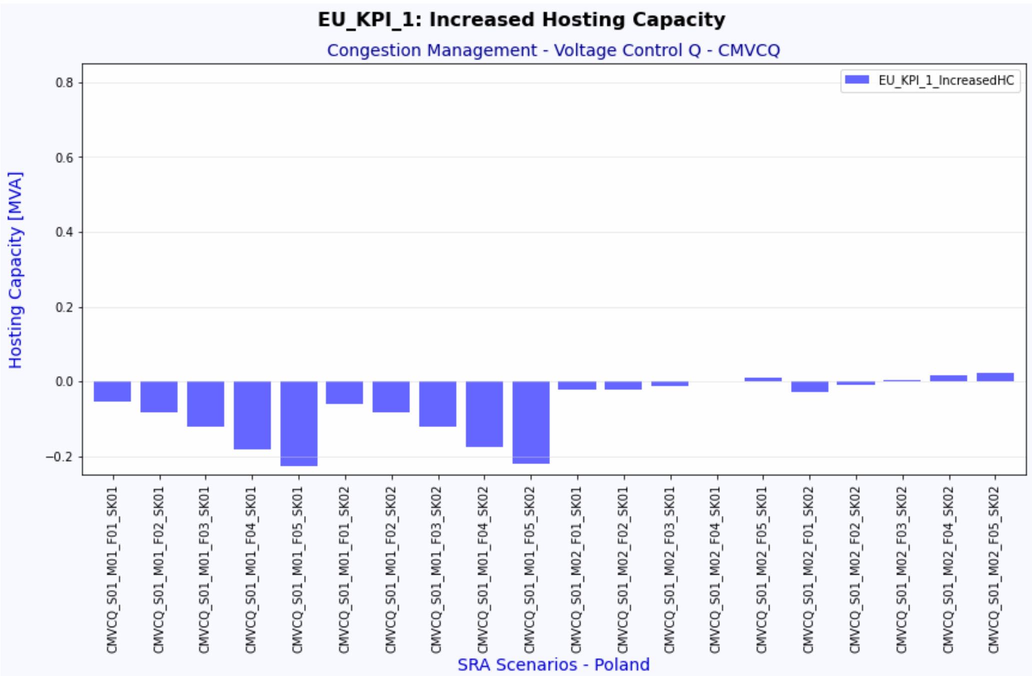


Figure 2.74 EU_KPI_1: Increase Hosting Capacity, for Congestion Management, Voltage Control using Reactive Power (CMVCQ)

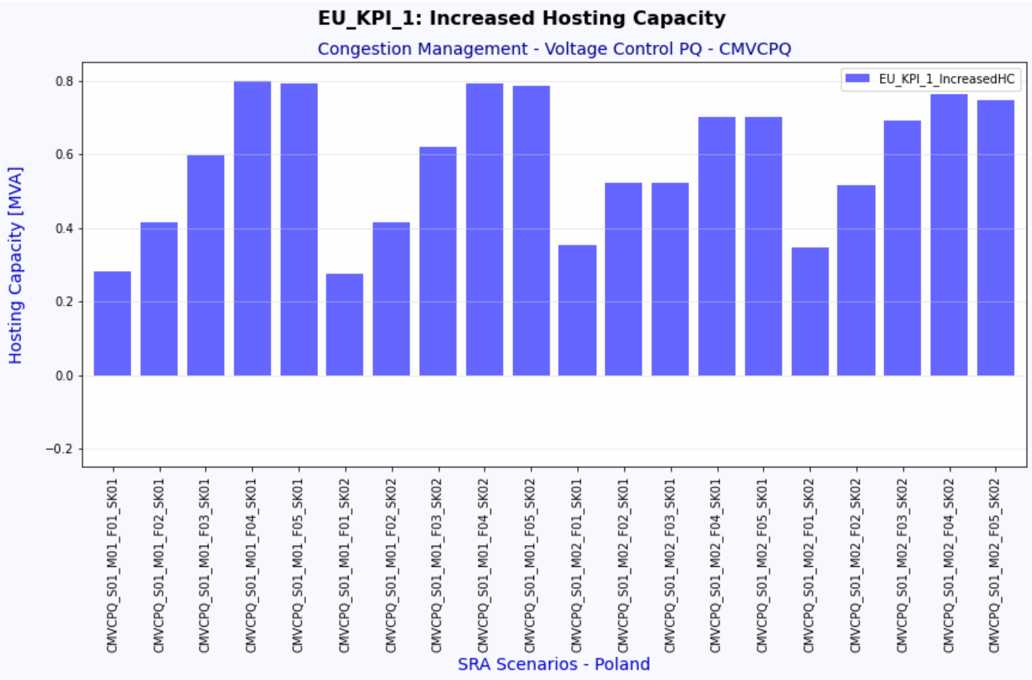
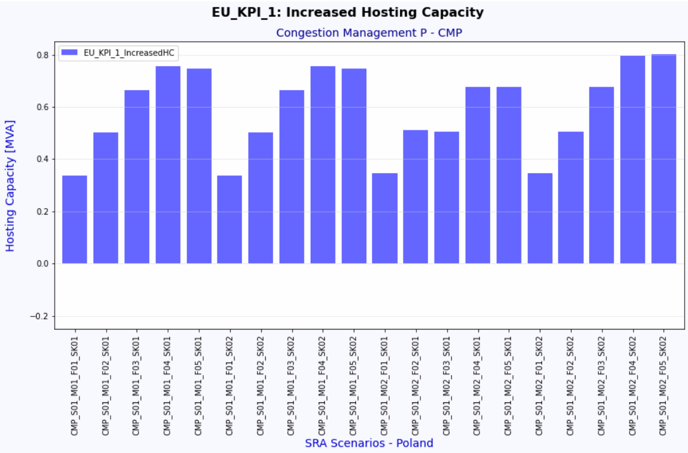
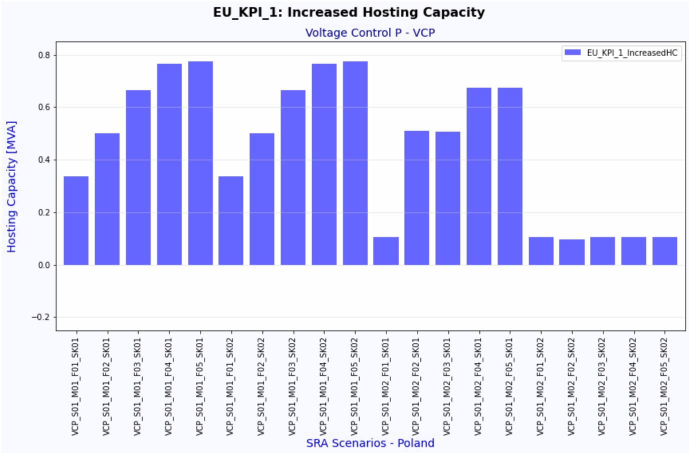


Figure 2.75 EU_KPI_1: Increase Hosting Capacity, for Congestion Management, Voltage Control using Active and Reactive Power (CMVCP)

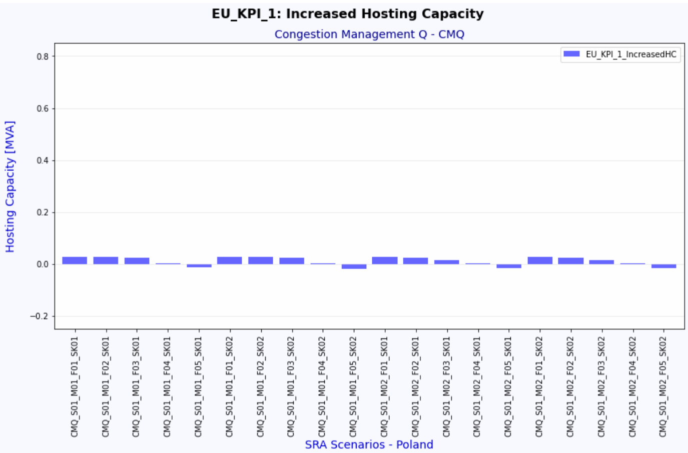
(a1)



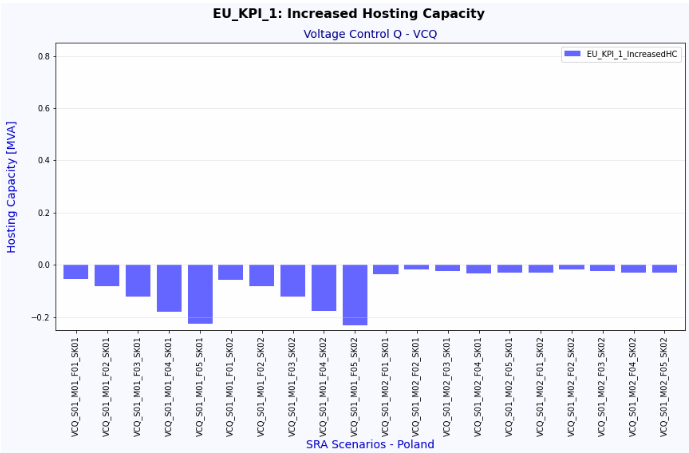
(b1)



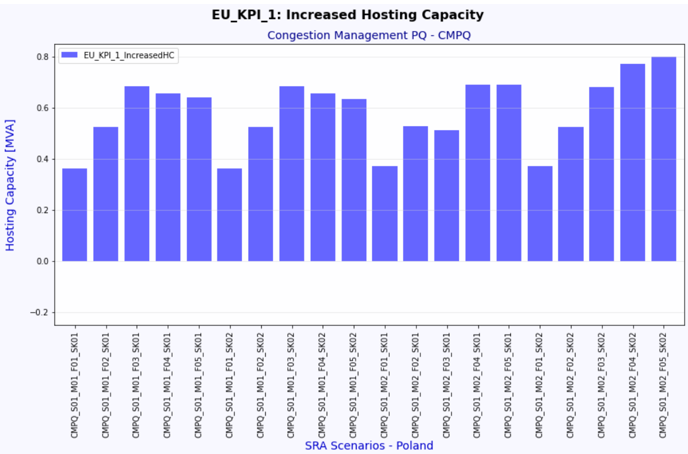
(a2)



(b2)



(a3)



(b3)

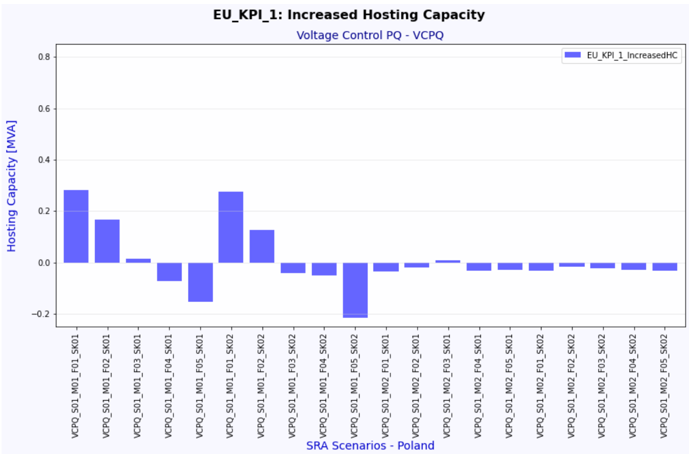


Figure 2.76 EU_KPI_1: Increase Hosting Capacity

Congestion Management: a1) Active Power, a2) Reactive Power, a3) Active and Reactive Power. Voltage Control: b1) Active Power, b2) Reactive Power, b3) Active and Reactive Power

2.5.1.2 German Demonstrator Net 1

This KPI measures the increase in Hosting Capacity resulting from the network improvements introduced by the market models in each scenario. Figure 2.77 and Figure 2.78 display the results of all scenarios, for CMVCP and CMVCQ, respectively, and taking into account the sensitivities specified in Table 2.19. Figure 2.79 serves as a comparative analysis, examining how the market dynamics are modified when active and reactive power are used simultaneously in the CMVCPQ market model. The different scenarios are plotted along the horizontal axis, while the vertical axes display, on the left side, the increase of Hosting Capacity in MVA.

Finally, it is important to note that other market models have been considered to analyze their impact on the network. Figure 2.80 depicts the results obtained for this KPI when using only Congestion Management (CM) or Voltage Control (VC).

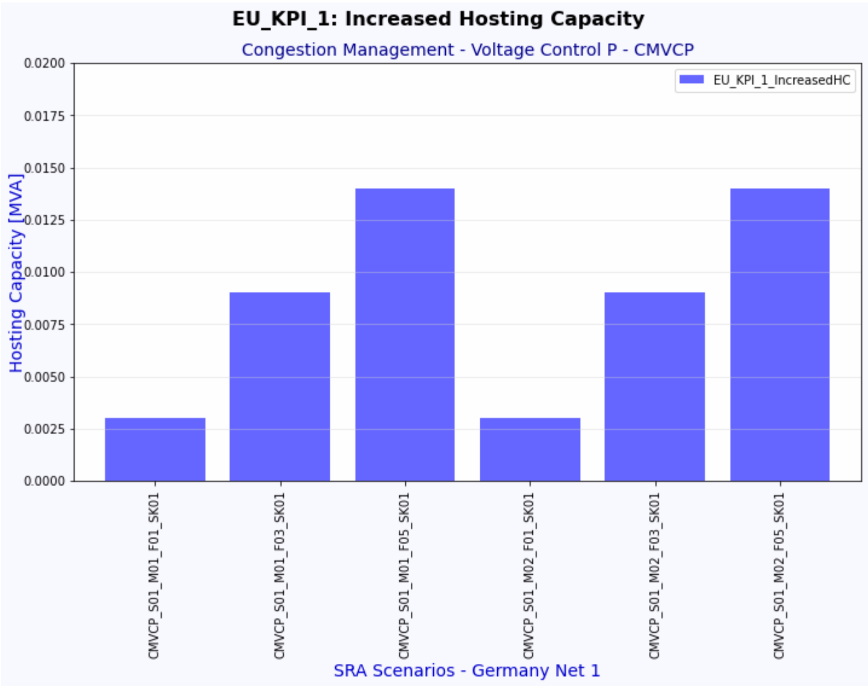


Figure 2.77 EU_KPI_1: Increase Hosting Capacity, for Congestion Management, Voltage Control using Active Power (CMVCP)

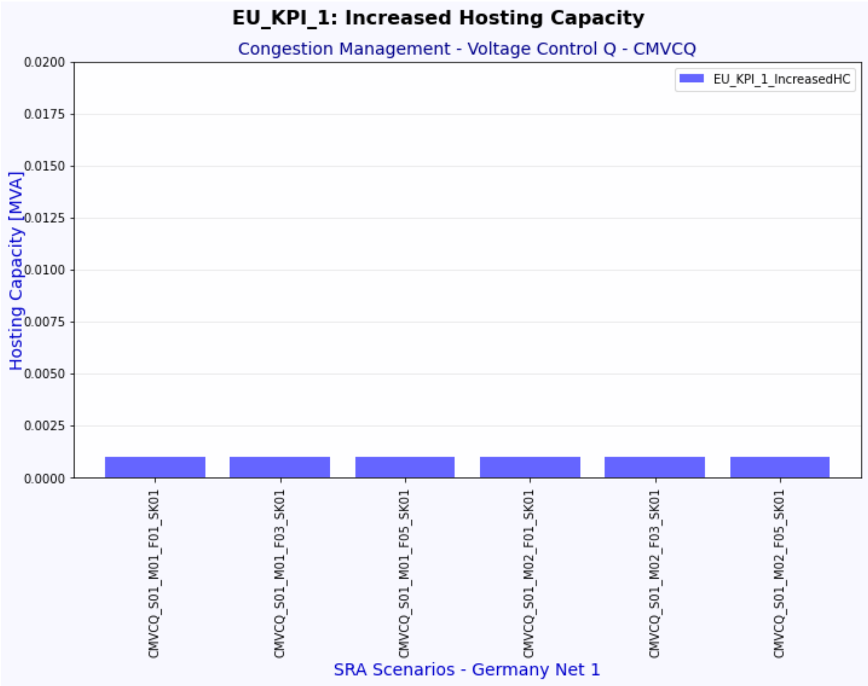


Figure 2.78 EU_KPI_1: Increase Hosting Capacity, for Congestion Management, Voltage Control using Reactive Power (CMVCQ)

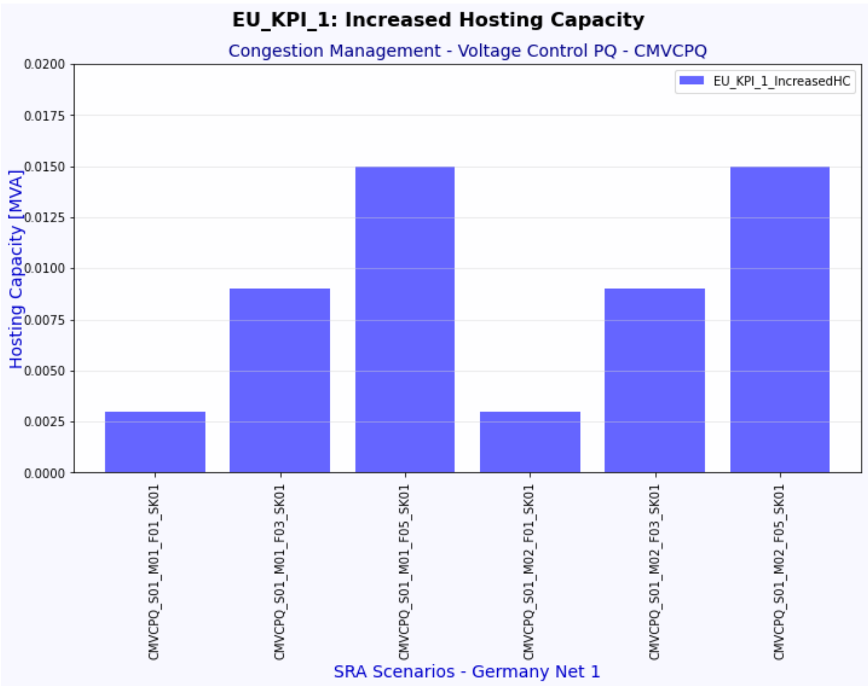


Figure 2.79 EU_KPI_1: Increase Hosting Capacity, for Congestion Management, Voltage Control using Active and Reactive Power (CMVCP)

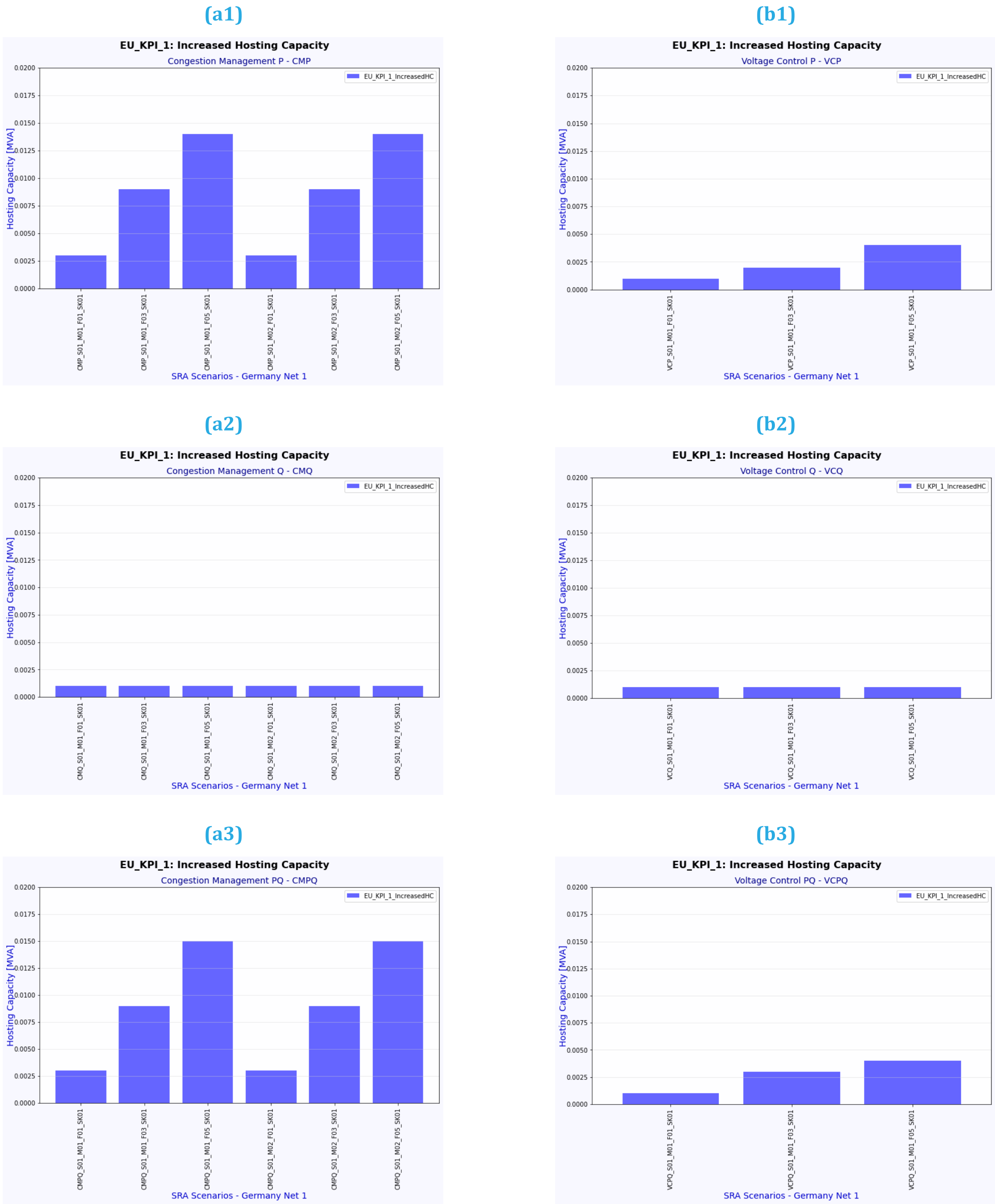


Figure 2.80 EU_KPI_1: Increase Hosting Capacity

Congestion Management: a1) Active Power, a2) Reactive Power, a3) Active and Reactive Power. Voltage Control: b1) Active Power, b2) Reactive Power, b3) Active and Reactive Power

2.5.1.3 German Demonstrator Net 2

This KPI measures the increase in Hosting Capacity resulting from the network improvements introduced by the market models in each scenario. Figure 2.81 and Figure 2.82 display the results of all scenarios, for CMVCP and CMVCQ, respectively, and taking into account the sensitivities specified in Table 2.29Table 2.9. Figure 2.83 serves as a comparative analysis, examining how the market dynamics are modified when active and reactive power are used simultaneously in the CMVCPQ market model. The different scenarios are plotted along the horizontal axis, while the vertical axes display, on the left side, the increase of Hosting Capacity in MVA.

Finally, it is important to note that other market models have been considered to analyze their impact on the network. Figure 2.84 depicts the results obtained for this KPI when using only Congestion Management (CM) or Voltage Control (VC).

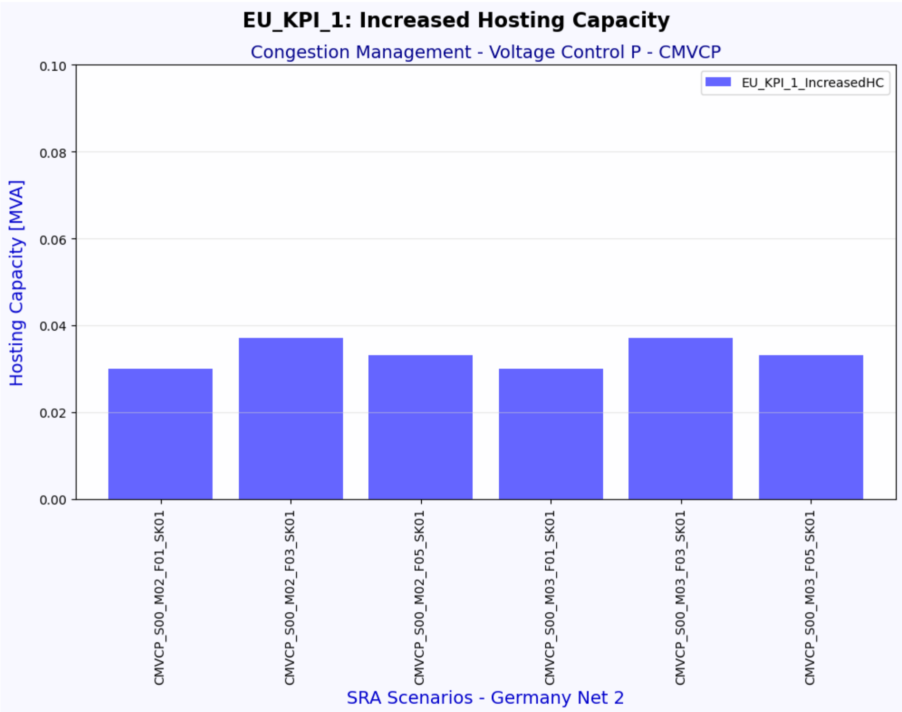


Figure 2.81 EU_KPI_1: Increase Hosting Capacity for Congestion Management, Voltage Control using Active Power (CMVCP)

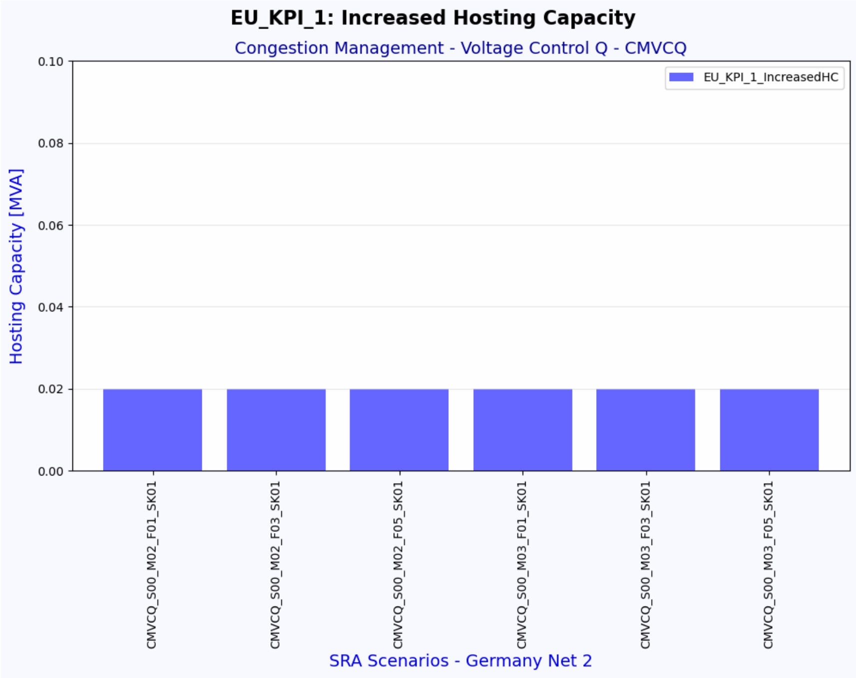


Figure 2.82 EU_KPI_1: Increase Hosting Capacity for Congestion Management, Voltage Control using Reactive Power (CMVCQ)

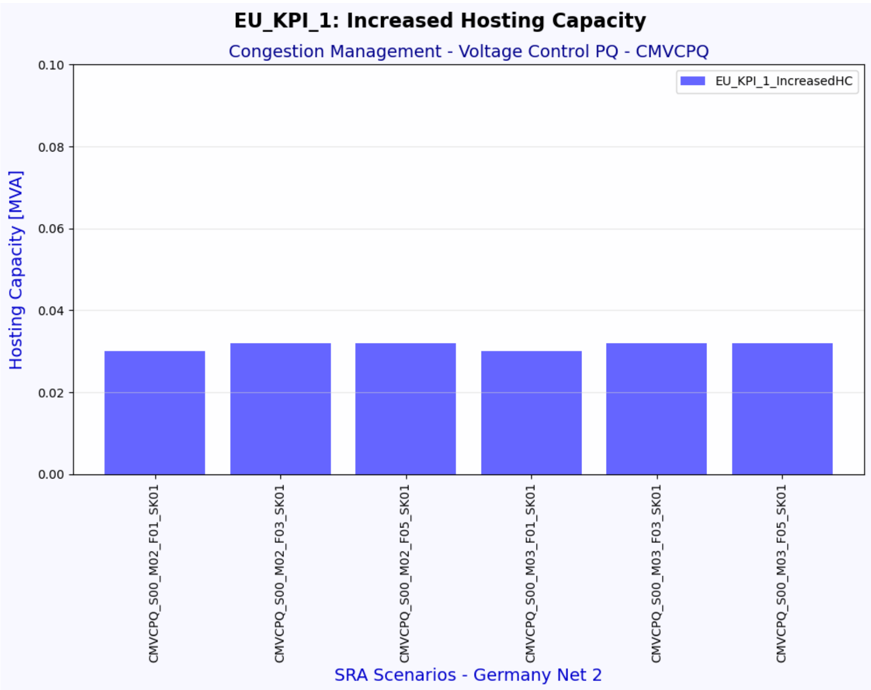
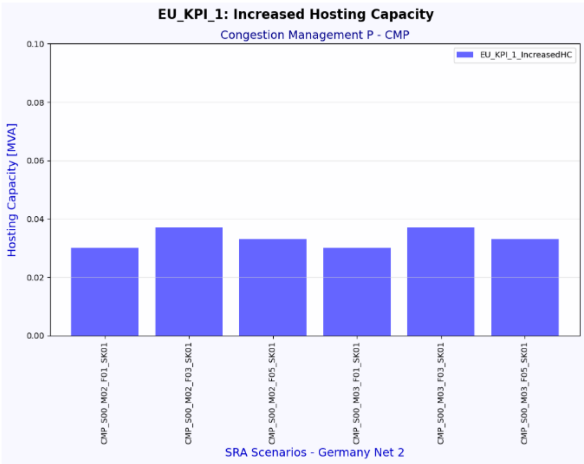
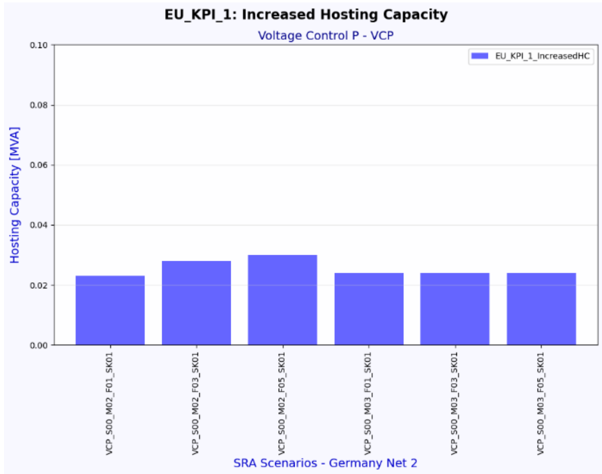


Figure 2.83 EU_KPI_1: Increase Hosting Capacity for Congestion Management, Voltage Control using Active and Reactive Power (CMVCPQ)

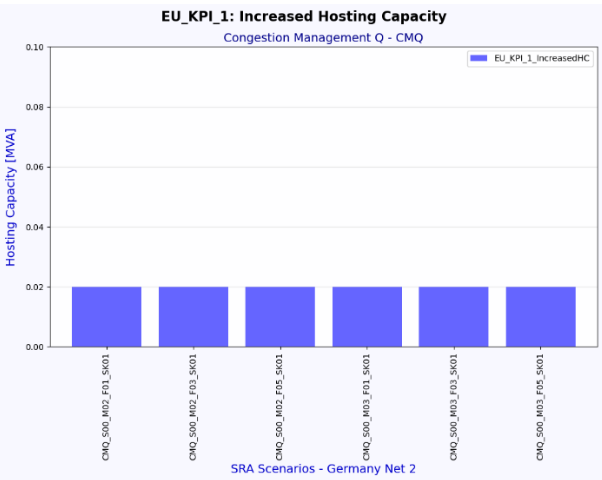
(a1)



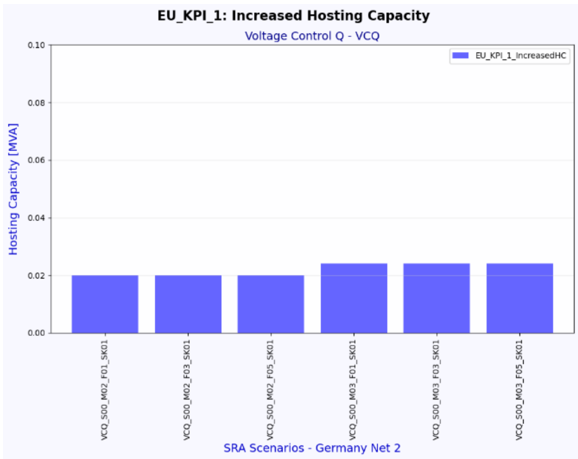
(b1)



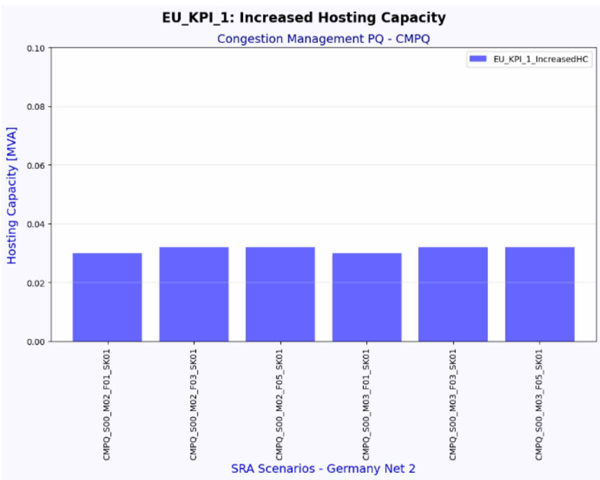
(a2)



(b2)



(a3)



(b3)

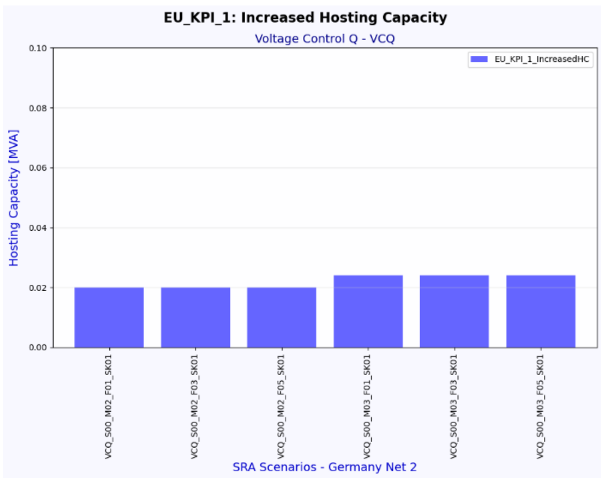


Figure 2.84 EU_KPI_1: Increase Hosting Capacity

Congestion Management: a1) Active Power, a2) Reactive Power, a3) Active and Reactive Power.

2.5.1.4 Portuguese Demonstrator

This KPI measures the increase in Hosting Capacity resulting from the network improvements introduced by the market models in each scenario. Figure 2.85 and Figure 2.86 display the results of all scenarios, for CMVCP and CMVCQ, respectively, and taking into account the SRA sensitivities specified in Section 2.4. Figure 2.87 serves as a comparative analysis, examining how the market dynamics are modified when active and reactive power are used simultaneously in the CMVCPQ market model. The different scenarios are plotted along the horizontal axis, while the vertical axes display, on the left side, the increase of Hosting Capacity in MVA.

Finally, it is important to note that other market models have been considered to analyze their impact on the network. Figure 2.88 depicts the results obtained for this KPI when using only Congestion Management (CM) or Voltage Control (VC).

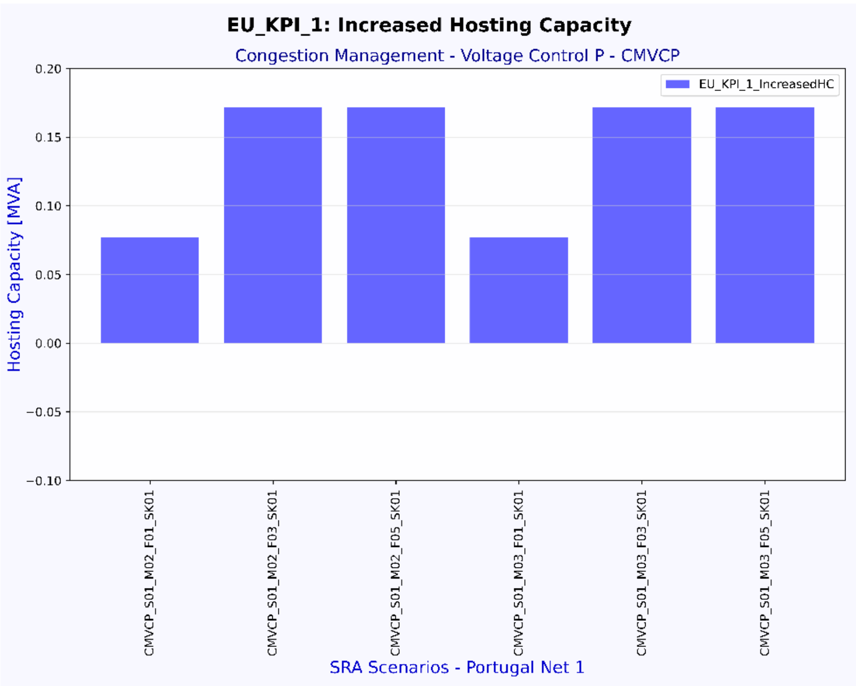


Figure 2.85 EU_KPI_1: Increase Hosting Capacity for Congestion Management, Voltage Control using Active Power (CMVCP)

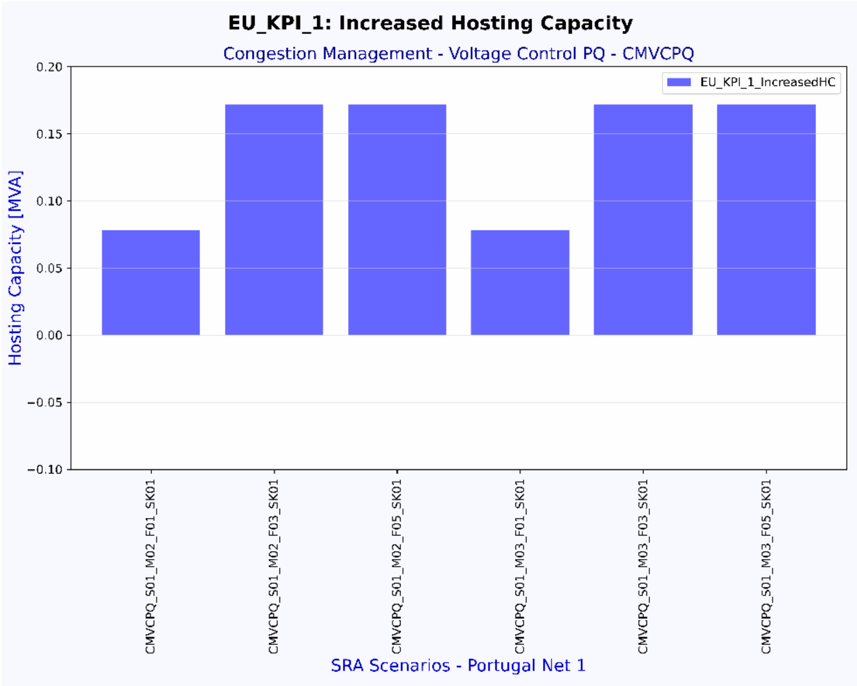


Figure 2.86 EU_KPI_1: Increase Hosting Capacity for Congestion Management, Voltage Control using Reactive Power (CMVCQ)

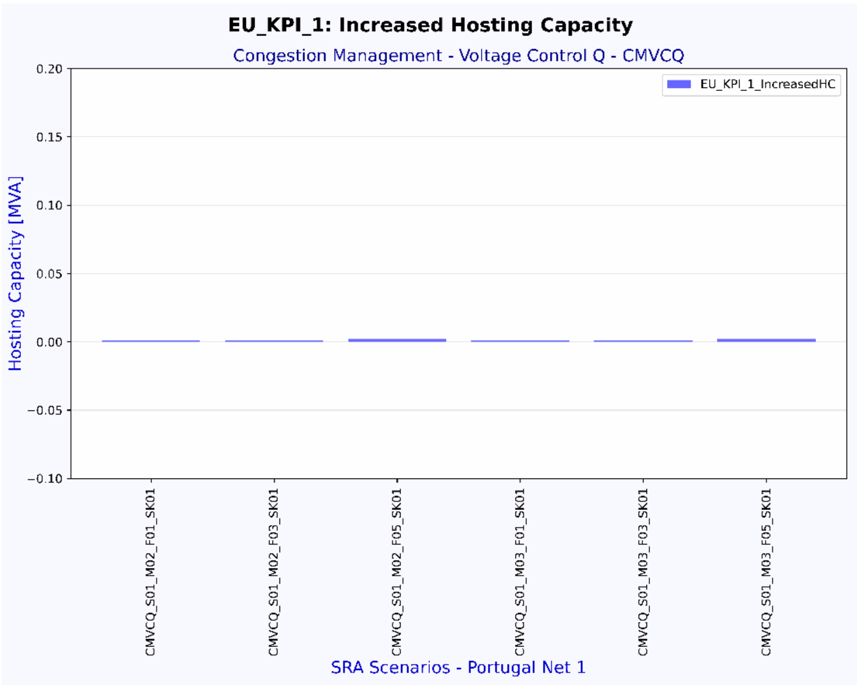


Figure 2.87 EU_KPI_1: Increase Hosting Capacity for Congestion Management, Voltage Control using Active and Reactive Power (CMVCP)

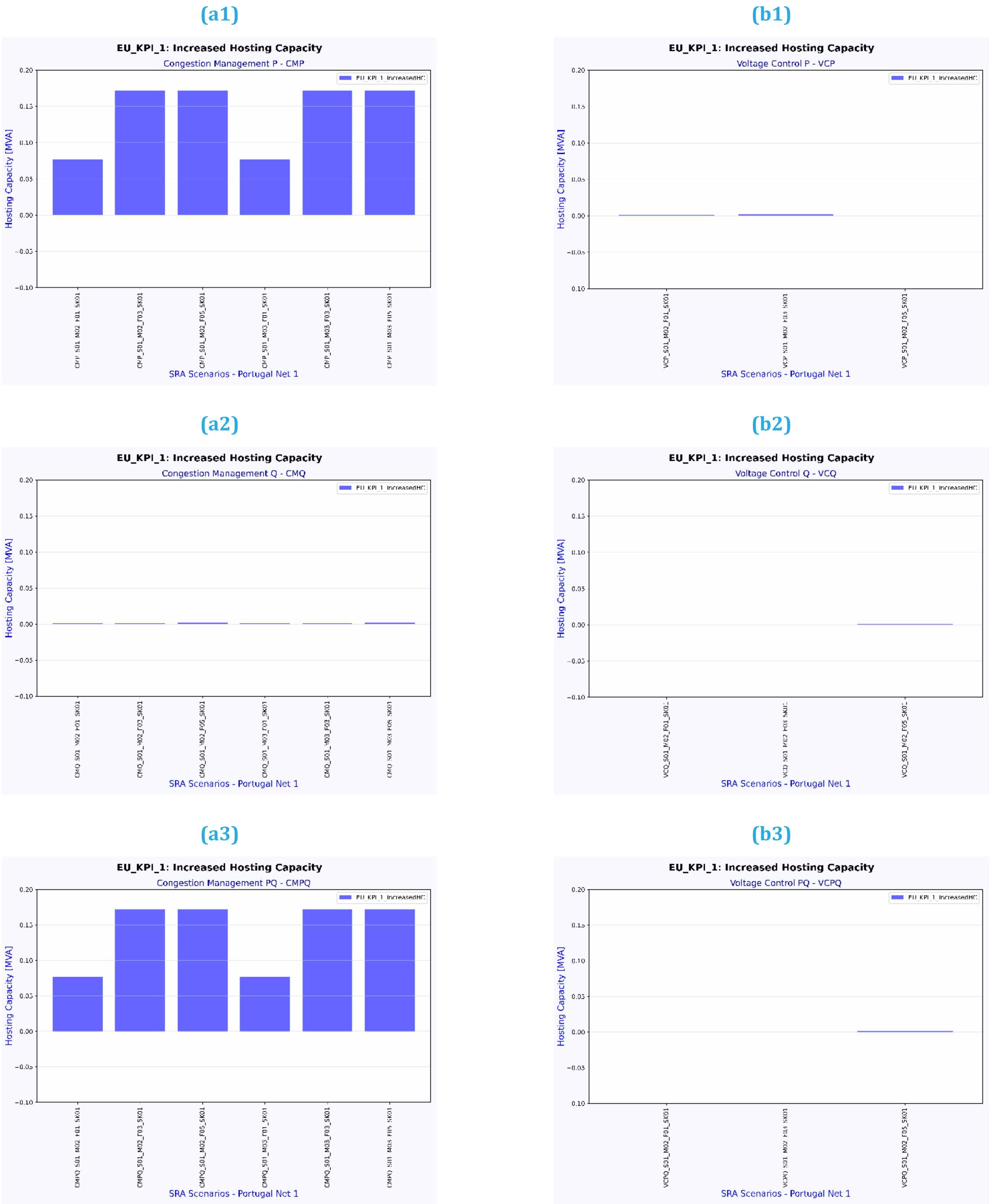


Figure 2.88 EU_KPI_1: Increase Hosting Capacity

Congestion Management: a1) Active Power, a2) Reactive Power, a3) Active and Reactive Power. Voltage Control: b1) Active Power, b2) Reactive Power, b3) Active and Reactive Power

2.5.2 EU_KPI_2: Increased of capacity and energy storage solution

2.5.2.1 Polish Demonstrator

This KPI measures the increase in Storage Solution resulting from the network improvements introduced by the market models in each scenario. For this purpose, the KPI has been divided into two components: the power term (Capacity Storage) and the energy term (Energy Storage). The power term provides a reference for the required power capacity in MVA. If the necessary equipment, such as power electronics, is available, it enables the manipulation of reactive power without consuming energy from the battery. On the other hand, the energy term offers a reference for the required storage capacity in MVAh and allows direct adjustments concerning active power utilization. Figure 2.89, Figure 2.90, Figure 2.91, and Figure 2.92 show the results for Increase of Capacity Storage, while, Figure 2.93, Figure 2.94, Figure 2.95, and Figure 2.96 show the results for Increase of Energy Storage.

Figure 2.89 and Figure 2.90 display the results of all scenarios for CMVCP and CMVCQ, respectively, taking into account the sensitivities specified in Table 2.9. Figure 2.91 serves as a comparative analysis, examining how the market dynamics are modified when active and reactive power are used simultaneously in the CMVCPQ market model, which presents a significant improvement in the KPI compared to the previous market models. The different scenarios are plotted along the horizontal axis, while the vertical axes display, on the left side, the increase of Capacity Storage in MVA. Furthermore, it is important to note that other market models have been considered to analyze their impact on the network. Figure 2.92 depicts the results obtained for this KPI when using only Congestion Management (CM) or Voltage Control (VC).

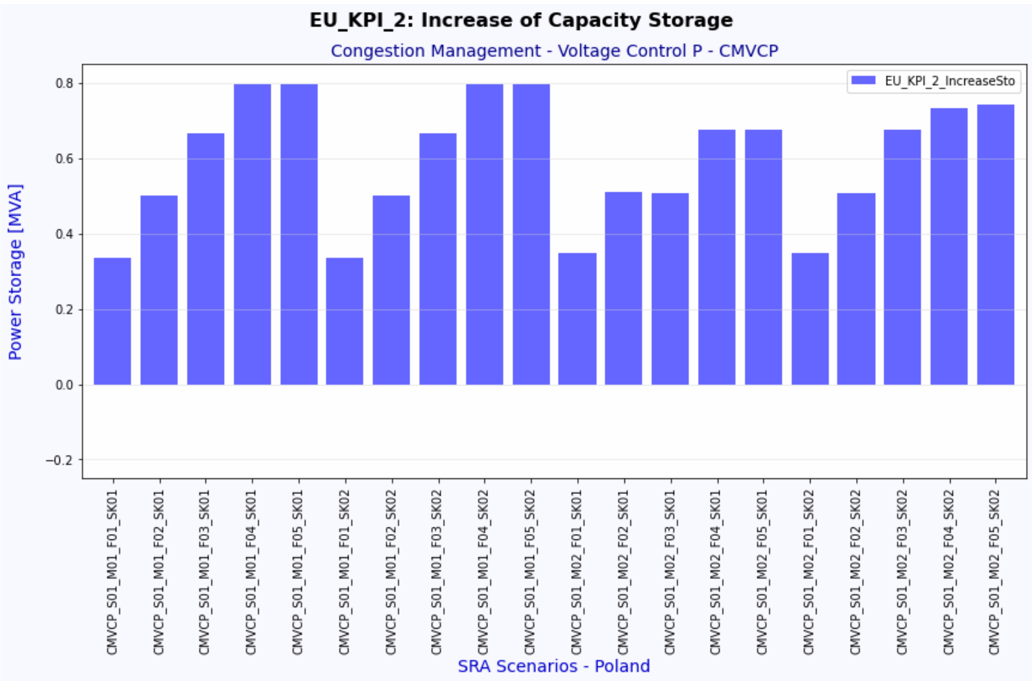


Figure 2.89 EU_KPI_2: Increased of capacity storage solution, for Congestion Management, Voltage Control using Active Power (CMVCP)

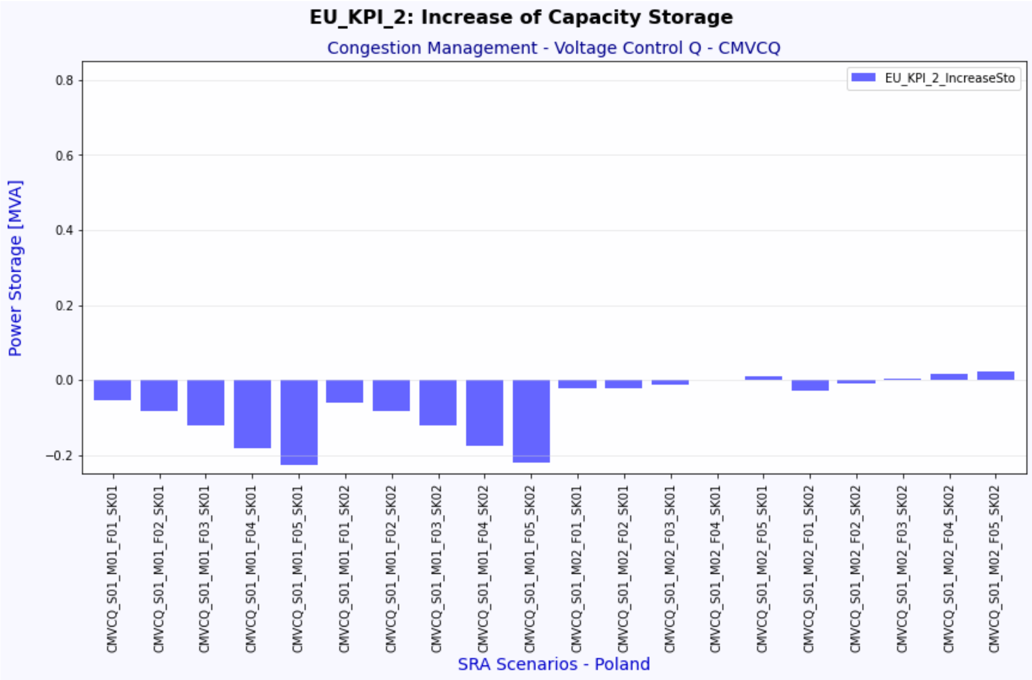


Figure 2.90 EU_KPI_2: Increased of capacity storage solution, for Congestion Management, Voltage Control using Reactive Power (CMVCQ)

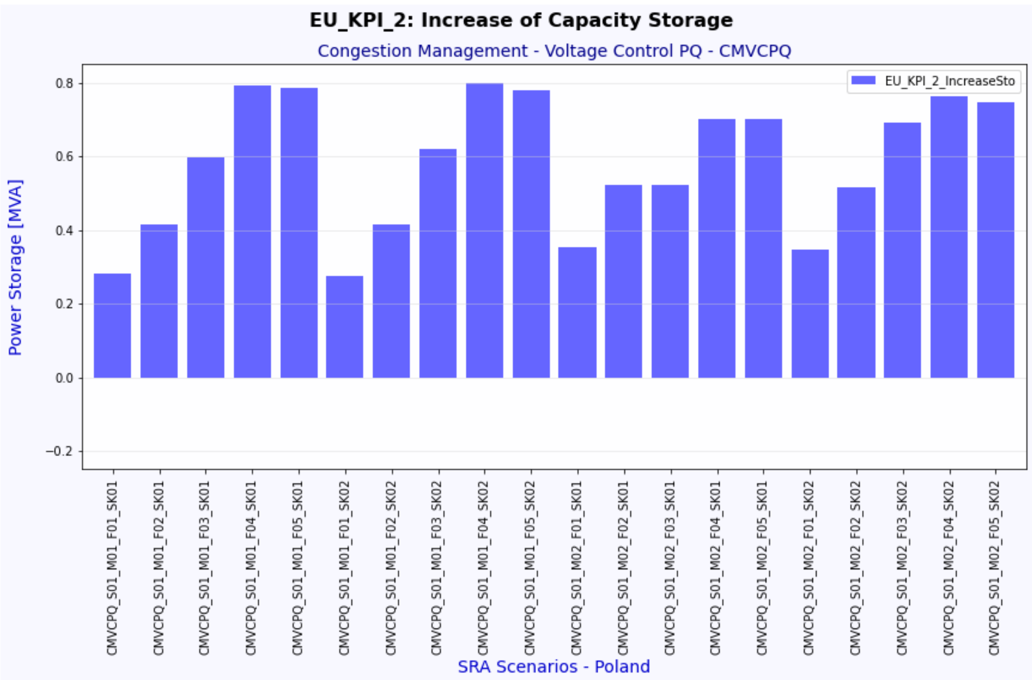
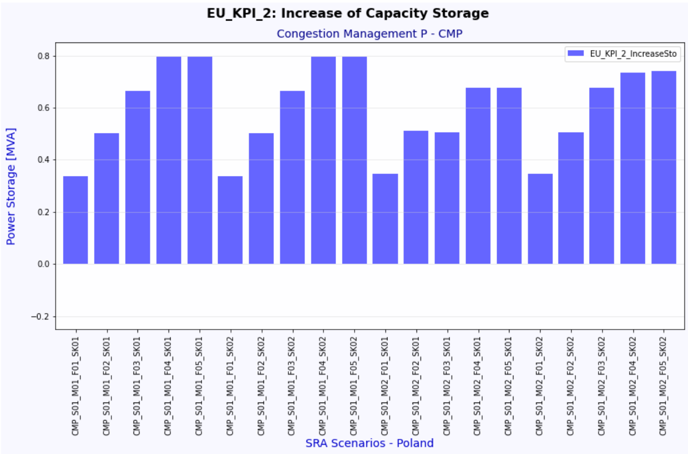
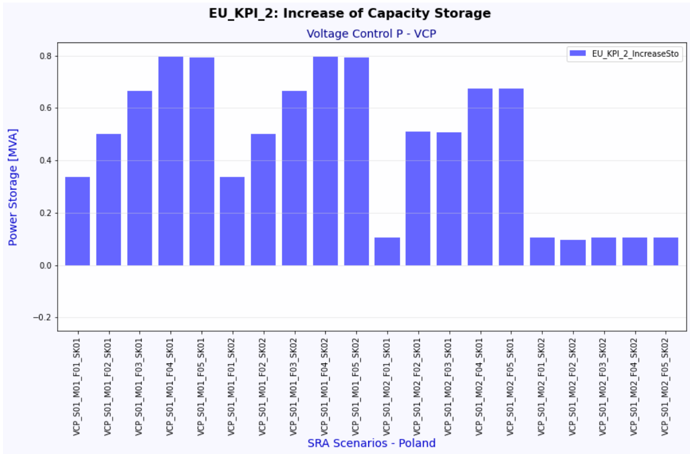


Figure 2.91 EU_KPI_2: Increased of capacity storage solution, for Congestion Management, Voltage Control using Active and Reactive Power (CMVCPQ)

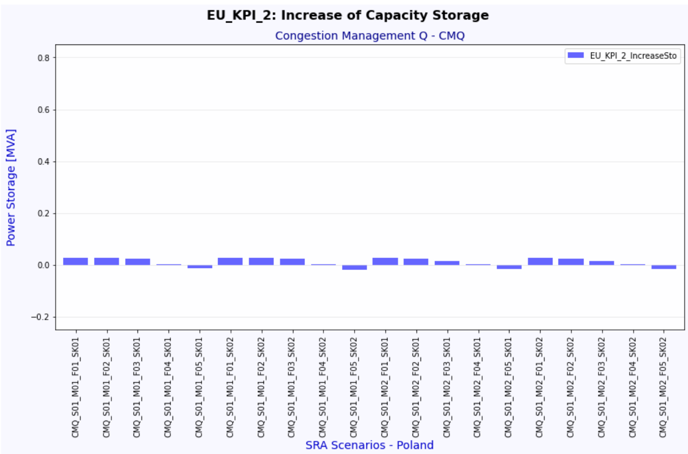
(a1)



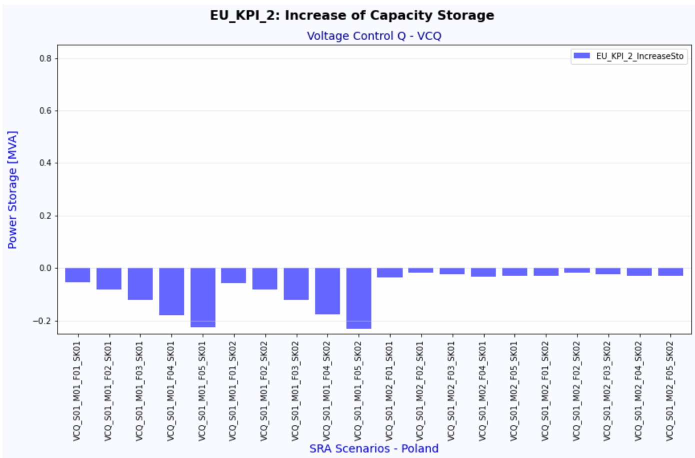
(b1)



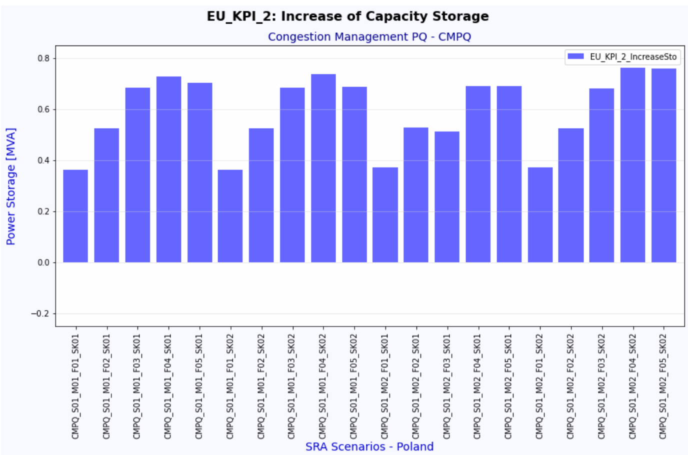
(a2)



(b2)



(a3)



(b3)

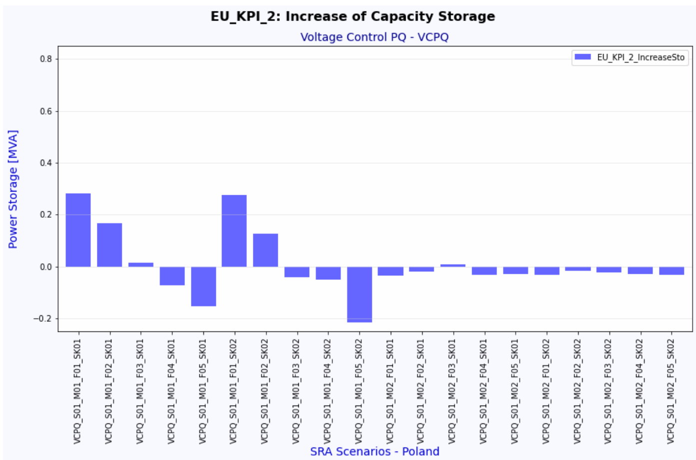


Figure 2.92 EU_KPI_2: Increased of capacity storage solution:

Congestion Management: a1) Active Power, a2) Reactive Power, a3) Active and Reactive Power. Voltage Control: b1) Active Power, b2) Reactive Power, b3) Active and Reactive Power

Figure 2.93, and Figure 2.94 display the results of all scenarios, for CMVCP and CMVCQ, respectively, and taking into account the sensitivities specified in Table 2.9. Figure 2.95 serves as a comparative analysis, examining how the market dynamics are modified when active and reactive power are used simultaneously in the CMVCPQ market model. The different scenarios are plotted along the horizontal axis, while the vertical axes display, on the left side, the increase of Energy Storage in MVAh.

In the case of the CMVCP market model results (Figure 2.93), it can be observed that as the sizes of the FSPs increase (F01 to F05), there is an improvement in the KPI throughout M01 and M02. Minor changes occur when there are modifications to the storage capacity SK01 and SK02.

In the case of the CMVCQ market model results (Figure 2.94), The KPI for M01 takes negative values, which means that the energy storage requirements after the market are higher than before the market. As indicated previously, it suggests that the utilization of reactive power alone may not be sufficient to mitigate criticalities effectively. On the other hand, the CMVCPQ market model presents a significant improvement in the KPI.

Furthermore, it is important to note that other market models have been considered to analyze their impact on the network. Figure 2.96 depicts the results obtained for this KPI when using only Congestion Management (CM) or Voltage Control (VC).

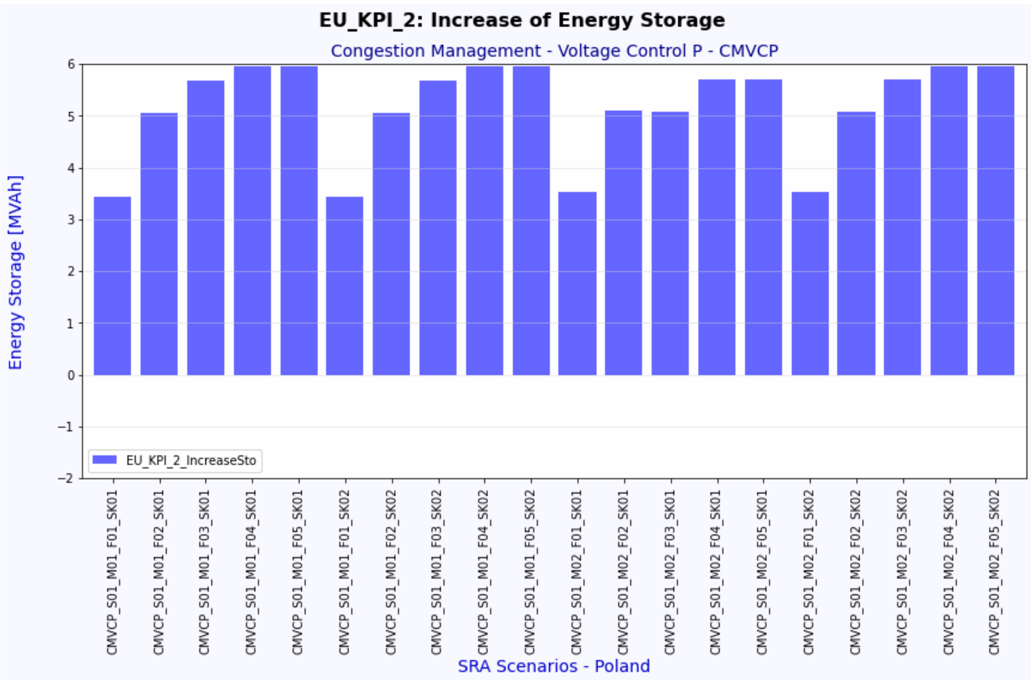


Figure 2.93 EU_KPI_2: Increased of energy storage solution for Congestion Management, Voltage Control using Active Power (CMVCP)

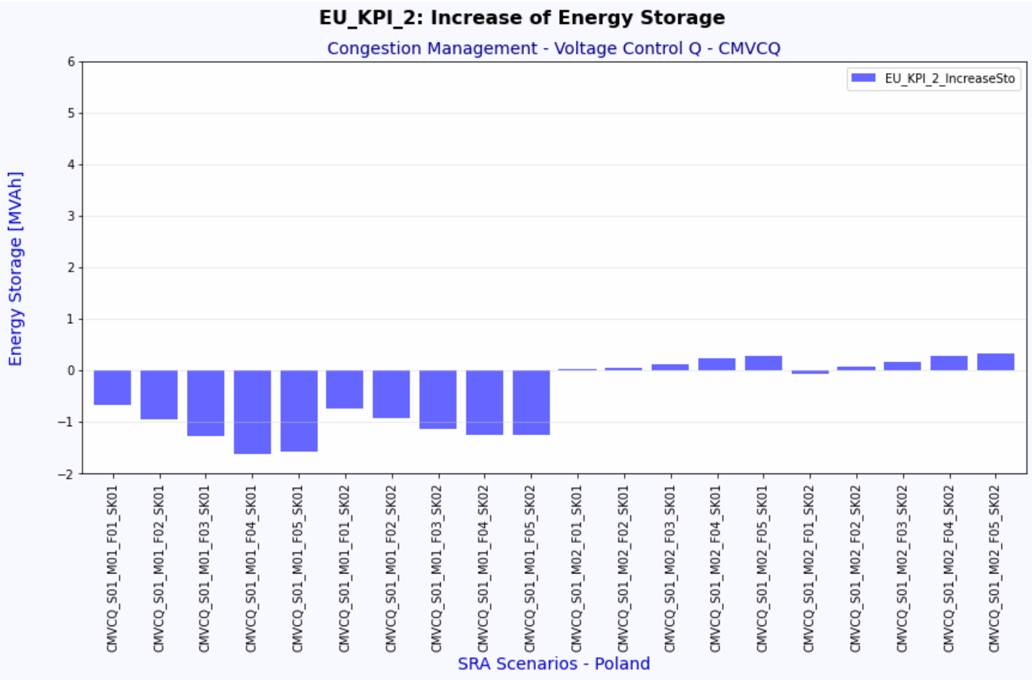


Figure 2.94 EU_KPI_2: Increased of energy storage solution for Congestion Management, Voltage Control using Reactive Power (CMVCQ)

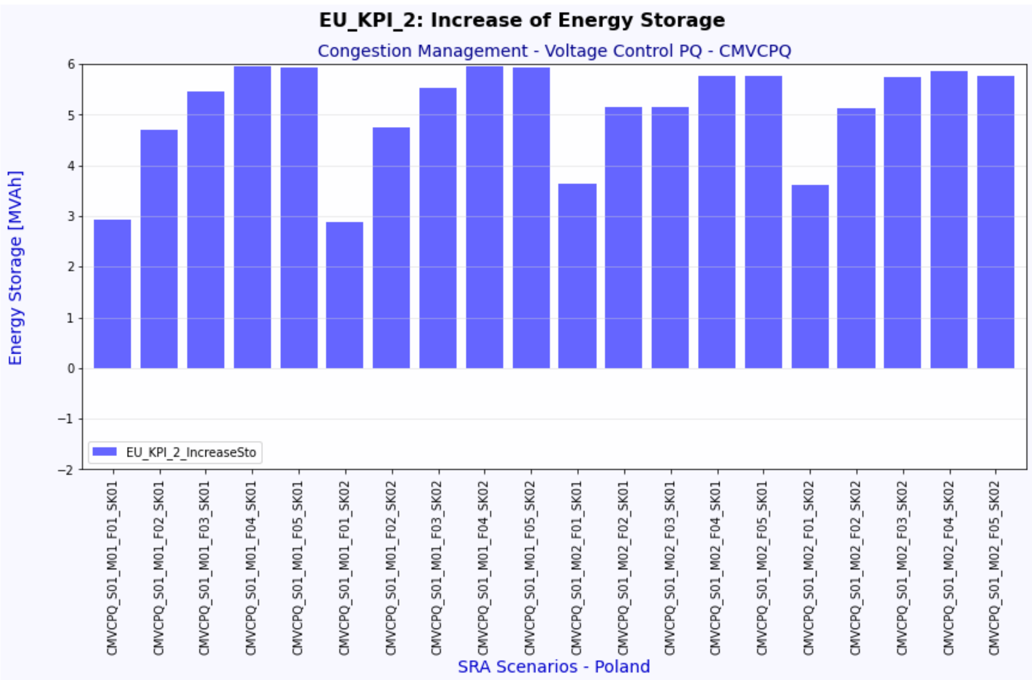
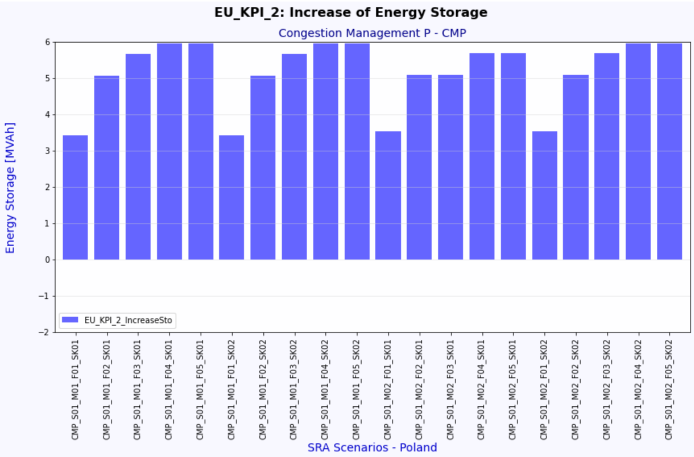
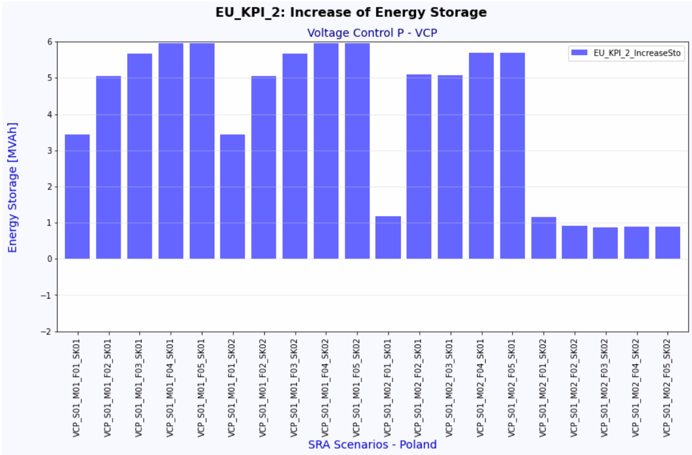


Figure 2.95 EU_KPI_2: Increased of energy storage solution for Congestion Management, Voltage Control using Active and Reactive Power (CMVCPQ)

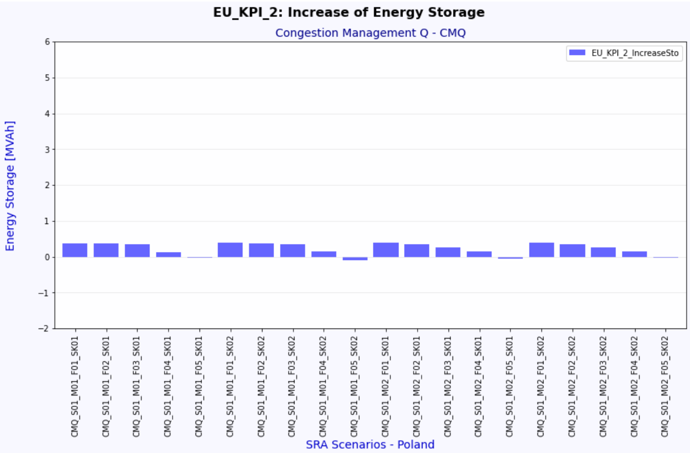
(a1)



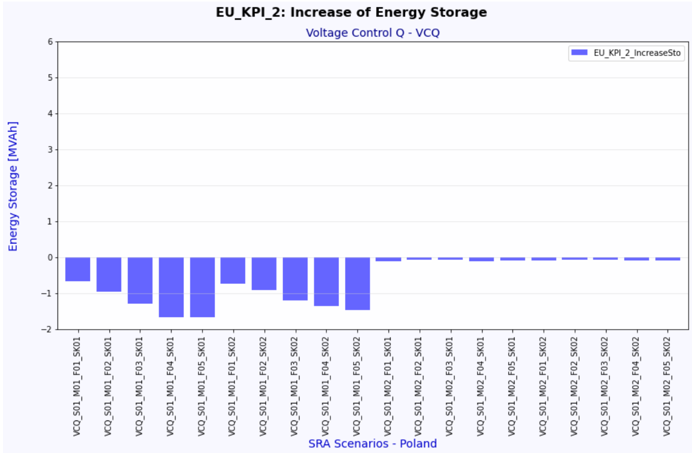
(b1)



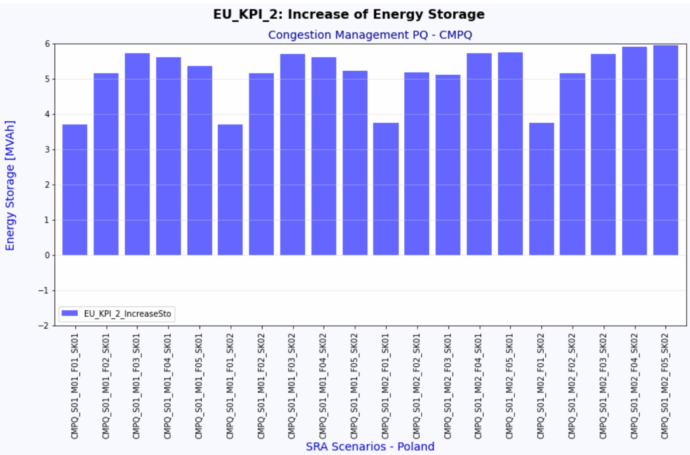
(a2)



(b2)



(a3)



(b3)

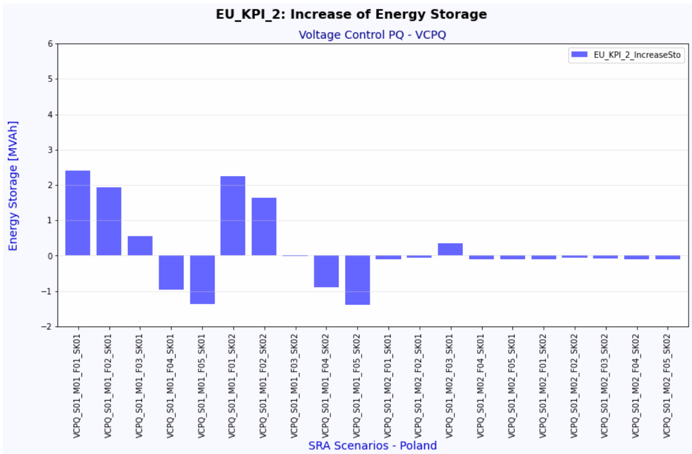


Figure 2.96 EU_KPI_2: Increased of energy storage solution:

Congestion Management: a1) Active Power, a2) Reactive Power, a3) Active and Reactive Power. Voltage Control: b1) Active Power, b2) Reactive Power, b3) Active and Reactive Power

2.5.2.2 German Demonstrator Net 1

This KPI measures the increase in Storage Solution resulting from the network improvements introduced by the market models in each scenario. For this purpose, the KPI has been divided into two components: the power term (Capacity Storage) and the energy term (Energy Storage). The power term provides a reference for the required power capacity in MVA. If the necessary equipment, such as power electronics, is available, it enables the manipulation of reactive power without consuming energy from the battery. On the other hand, the energy term offers a reference for the required storage capacity in MVAh and allows direct adjustments concerning active power utilization. Figure 2.97, Figure 2.98, Figure 2.99, and Figure 2.100 show the results for Increase of Capacity Storage, while, Figure 2.101, Figure 2.102, Figure 2.103, and Figure 2.104 show the results for Increase of Energy Storage.

Figure 2.97and Figure 2.98 display the results of all scenarios for CMVCP and CMVCQ, respectively, and taking into account the sensitivities specified in Table 2.19. Figure 2.99Figure 2.91 serves as a comparative analysis, examining how the market dynamics are modified when active and reactive power are used simultaneously in the CMVCPQ market model, which presents a significant improvement in the KPI compared to the previous market models. The different scenarios are plotted along the horizontal axis, while the vertical axes display, on the left side, the increase of Capacity Storage in MVA. Furthermore, it is important to note that other market models have been considered to analyze their impact on the network. Figure 2.100 depicts the results obtained for this KPI when using only Congestion Management (CM) or Voltage Control (VC).

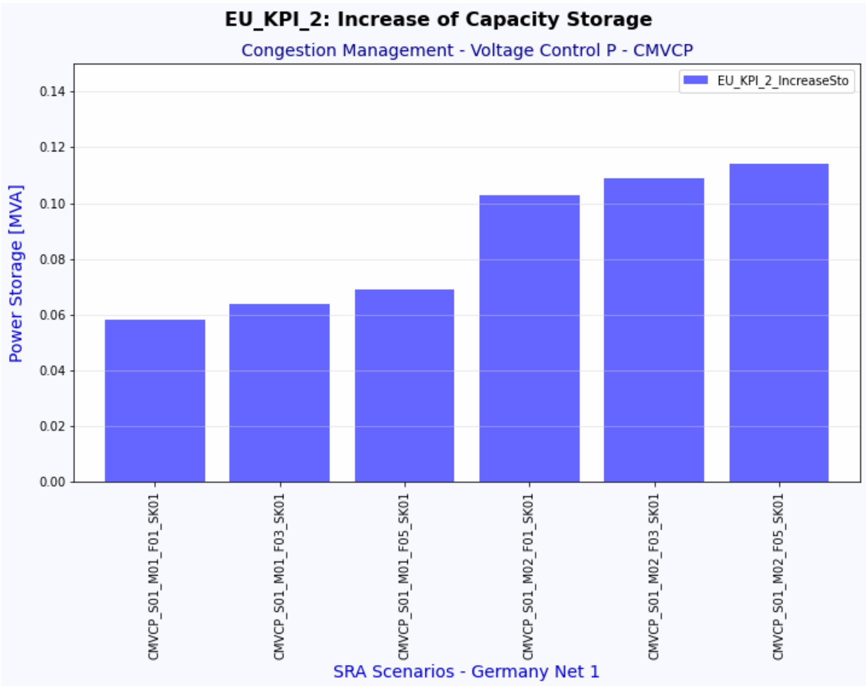


Figure 2.97 EU_KPI_2: Increased of capacity storage solution, for Congestion Management, Voltage Control using Active Power (CMVCP)

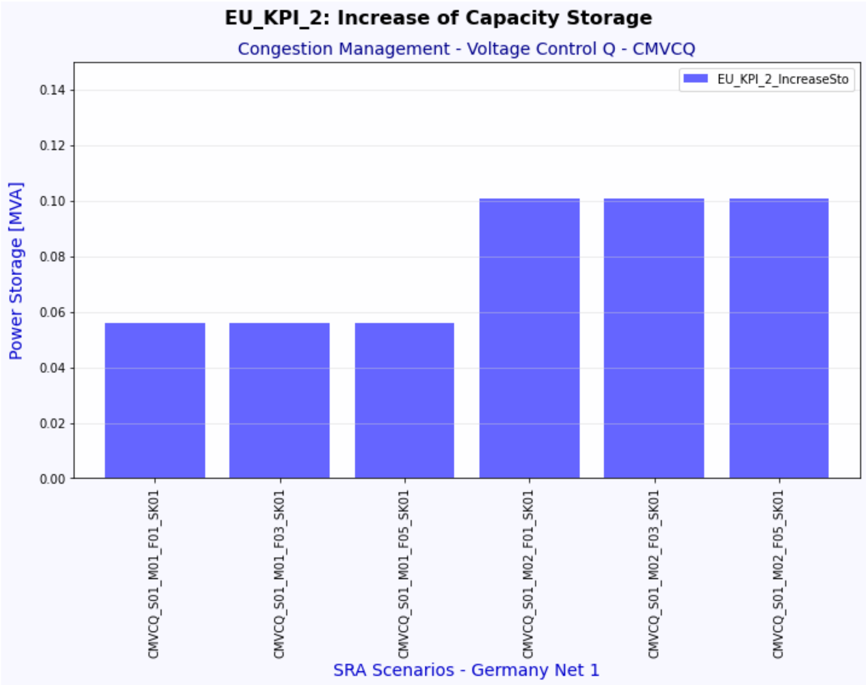


Figure 2.98 EU_KPI_2: Increased of capacity storage solution, for Congestion Management, Voltage Control using Reactive Power (CMVCQ)

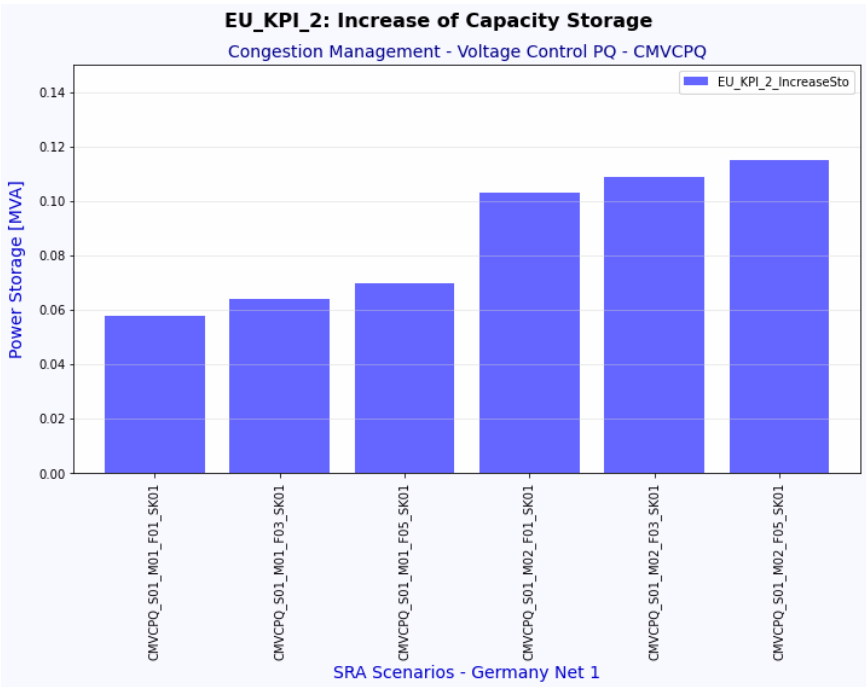
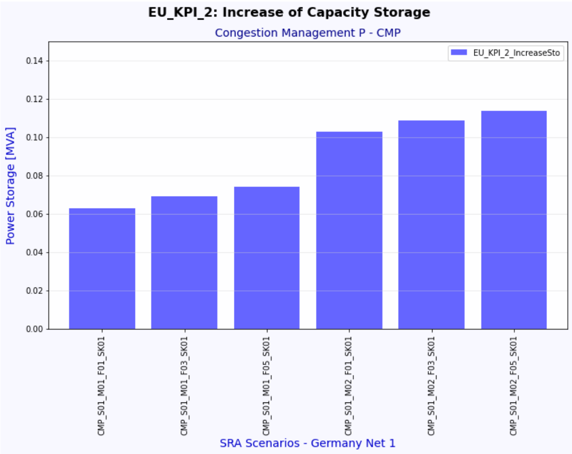
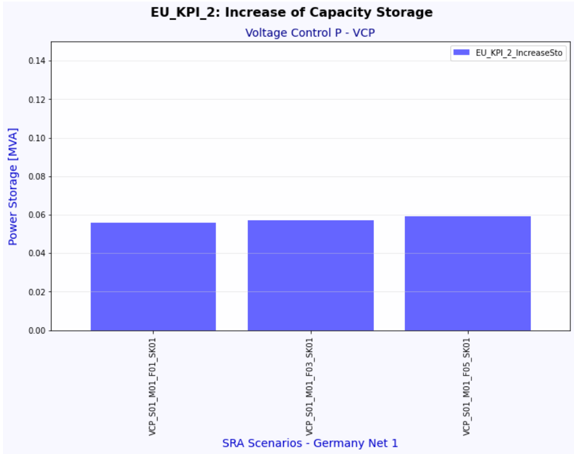


Figure 2.99 EU_KPI_2: Increased of capacity storage solution, for Congestion Management, Voltage Control using Active and Reactive Power (CMVCPQ)

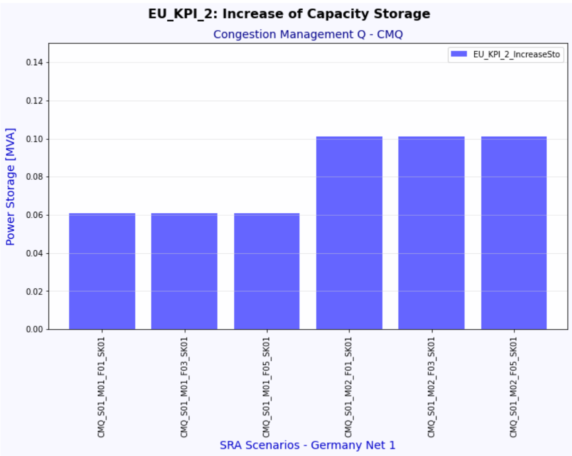
(a1)



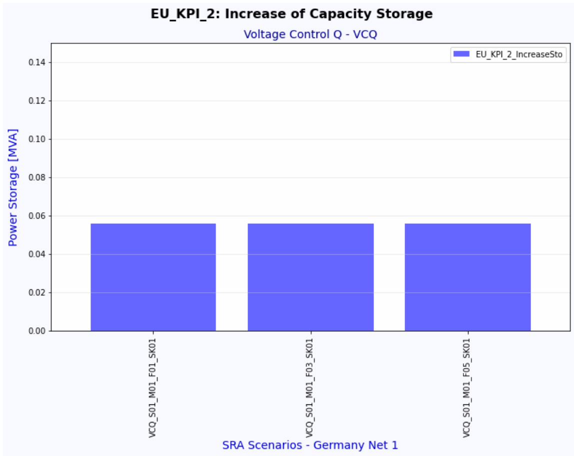
(b1)



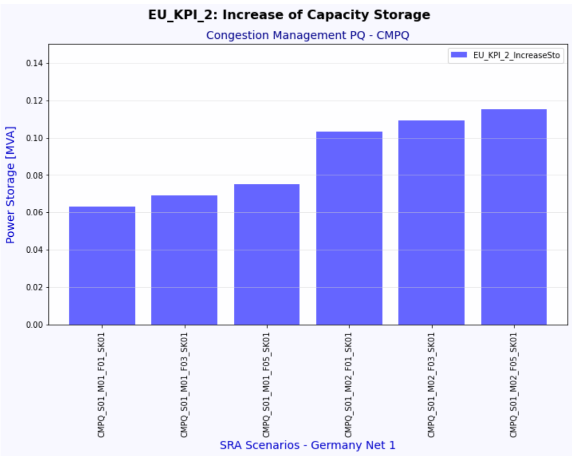
(a2)



(b2)



(a3)



(b3)

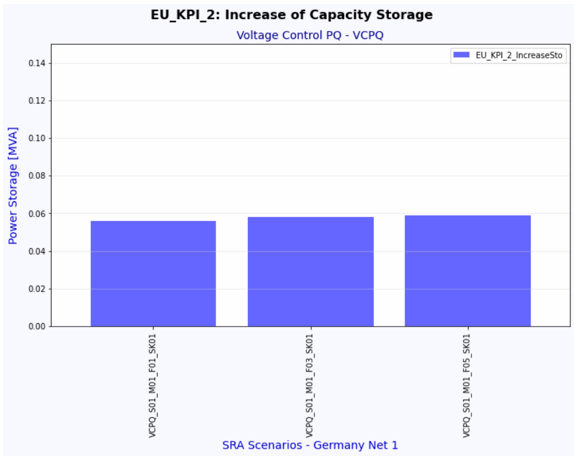


Figure 2.100 EU_KPI_2: Increased of capacity storage solution:

Congestion Management: a1) Active Power, a2) Reactive Power, a3) Active and Reactive Power.
Voltage Control: b1) Active Power, b2) Reactive Power, b3) Active and Reactive Power

Figure 2.101 and Figure 2.102 display the results of all scenarios for CMVCP and CMVCQ, respectively, and taking into account the sensitivities specified in Table 2.19. Figure 2.103 serves as a comparative analysis, examining how the market dynamics are modified when active and reactive power are used simultaneously in the CMVCPQ market model. The different scenarios are plotted along the horizontal axis, while the vertical axes display, on the left side, the increase of Energy Storage in MVAh.

Furthermore, it is important to note that other market models have been considered to analyze their impact on the network. Figure 2.104 depicts the results obtained for this KPI when using only Congestion Management (CM) or Voltage Control (VC).

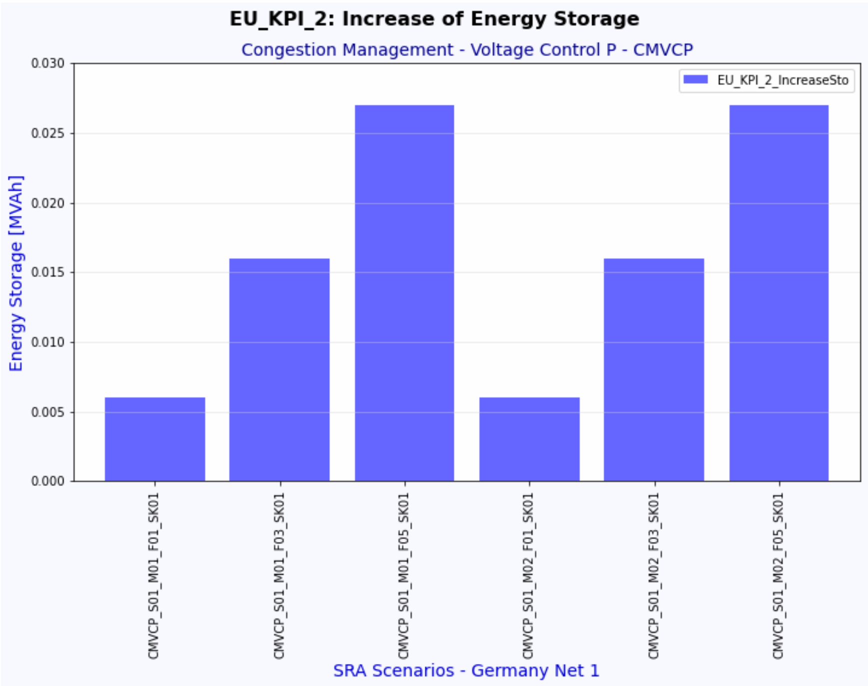


Figure 2.101 EU_KPI_2: Increased of energy storage solution for Congestion Management, Voltage Control using Active Power (CMVCP)

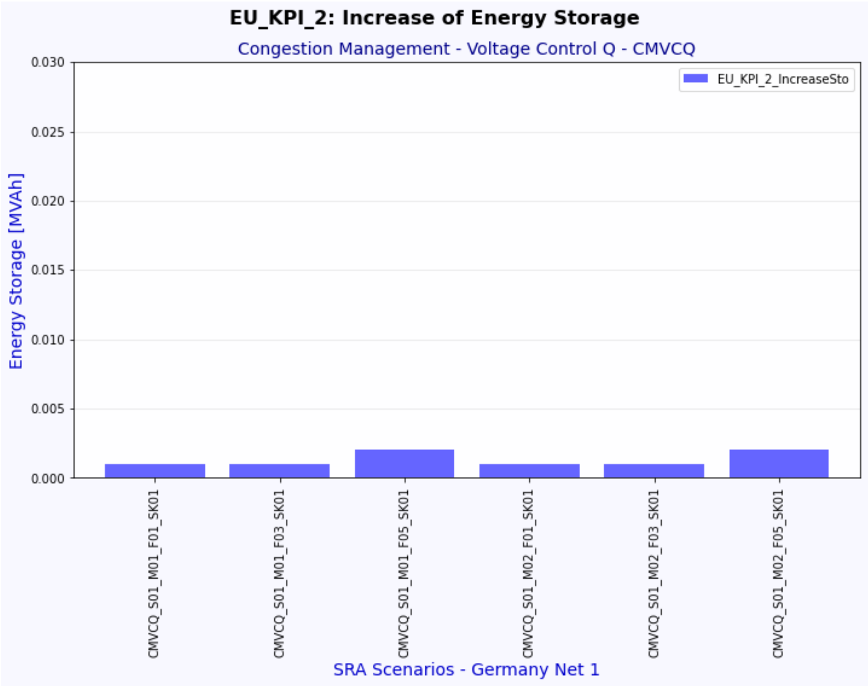


Figure 2.102 EU_KPI_2: Increased of energy storage solution for Congestion Management, Voltage Control using Reactive Power (CMVCQ)

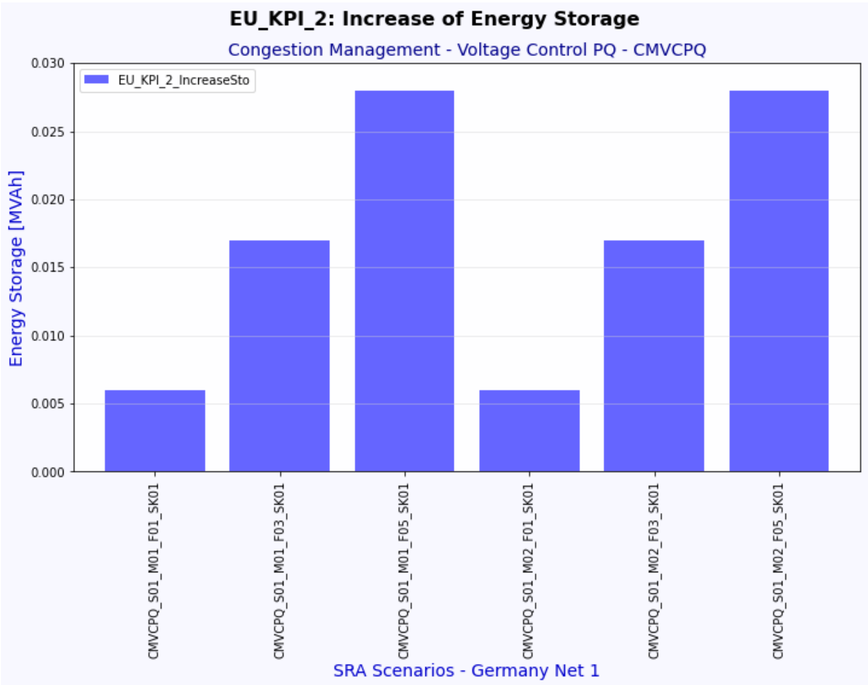
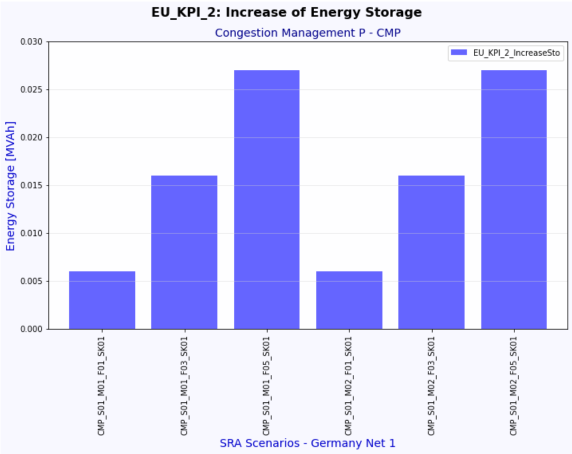
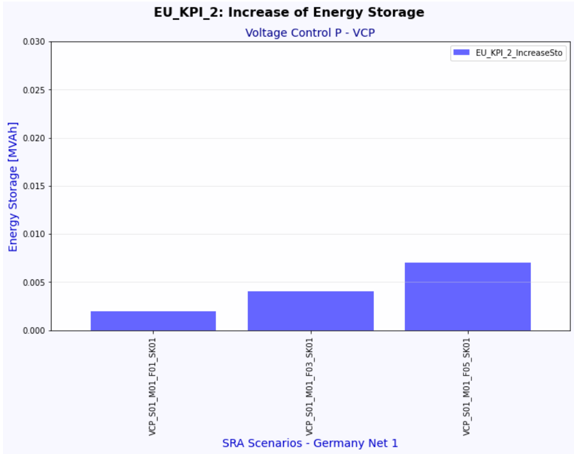


Figure 2.103 EU_KPI_2: Increased of energy storage solution for Congestion Management, Voltage Control using Active and Reactive Power (CMVCPQ)

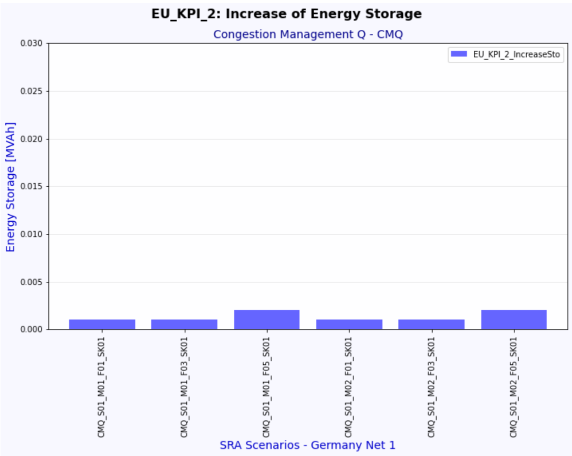
(a1)



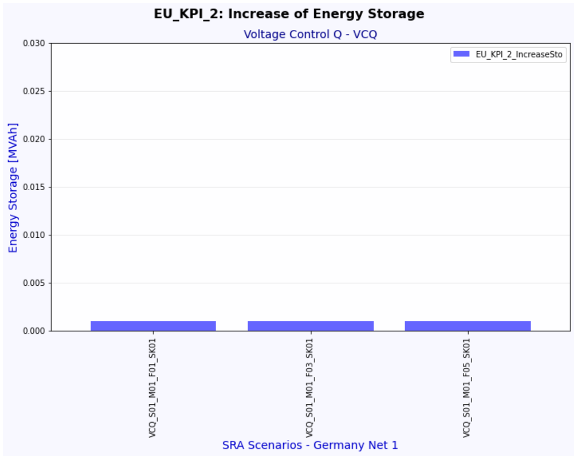
(b1)



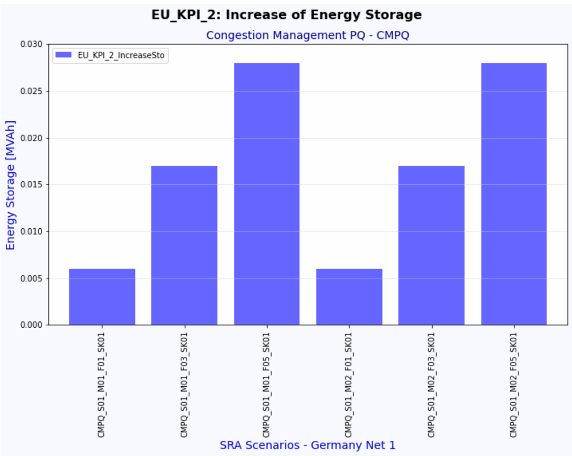
(a2)



(b2)



(a3)



(b3)

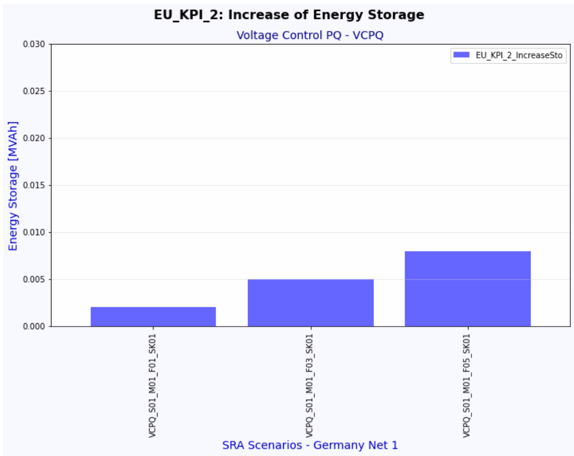


Figure 2.104 EU_KPI_2: Increased of energy storage solution:

Congestion Management: a1) Active Power, a2) Reactive Power, a3) Active and Reactive Power. Voltage Control: b1) Active Power, b2) Reactive Power, b3) Active and Reactive Power

2.5.2.3 German Demonstrator Net 2

This KPI measures the increase in Storage Solution resulting from the network improvements introduced by the market models in each scenario. For this purpose, the KPI has been divided into two components: the power term (Capacity Storage) and the energy term (Energy Storage). The power term provides a reference for the required power capacity in MVA. If the necessary equipment, such as power electronics, is available, it enables the manipulation of reactive power without consuming energy from the battery. On the other hand, the energy term offers a reference for the required storage capacity in MVAh and allows direct adjustments concerning active power utilization. Figure 2.105, Figure 2.106, Figure 2.107, and Figure 2.108 show the results for Increase of Capacity Storage, while, Figure 2.109, Figure 2.110, Figure 2.111, and Figure 2.112 show the results for Increase of Energy Storage.

Figure 2.105 and Figure 2.106 display the results for CMVCP and CMVCQ, considering the SRA sensitivities specified in Table 2.29. Figure 2.107Figure 2.91 serves as a comparative analysis, examining how the market dynamics are modified when active and reactive power are used simultaneously in the CMVCPQ market model, which presents a significant improvement in the KPI compared to the previous market models. The different scenarios are plotted along the horizontal axis, while the vertical axes display, on the left side, the increase of Capacity Storage in MVA. Furthermore, it is important to note that other market models have been considered to analyze their impact on the network. Figure 2.108 depicts the results obtained for this KPI when using only Congestion Management (CM) or Voltage Control (VC).

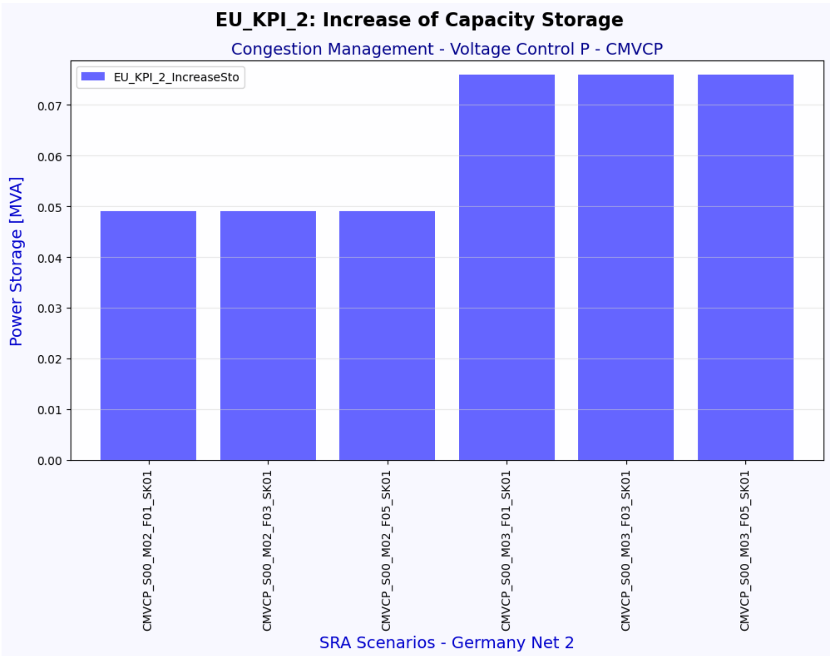


Figure 2.105 EU_KPI_2: Increased of capacity storage solution, for Congestion Management, Voltage Control using Active Power (CMVCP)

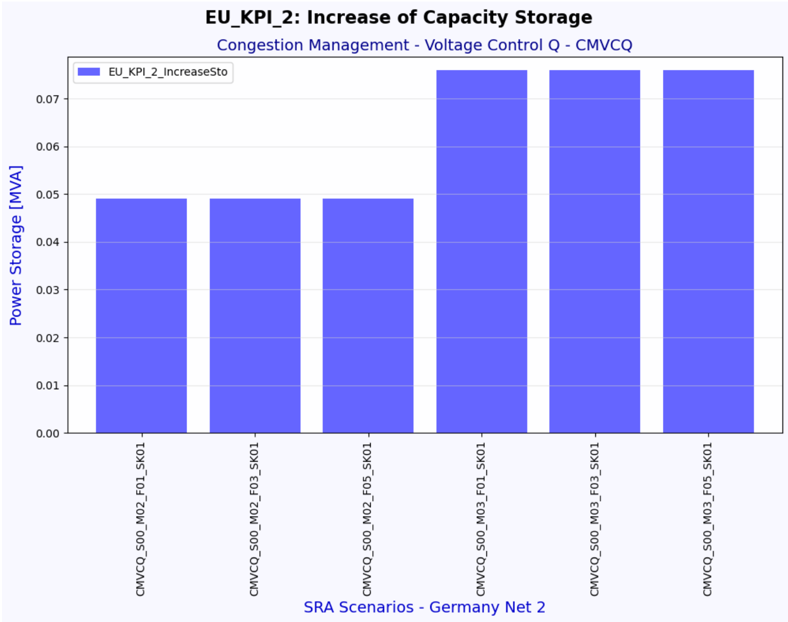


Figure 2.106 EU_KPI_2: Increased of capacity storage solution, for Congestion Management, Voltage Control using Reactive Power (CMVCQ)

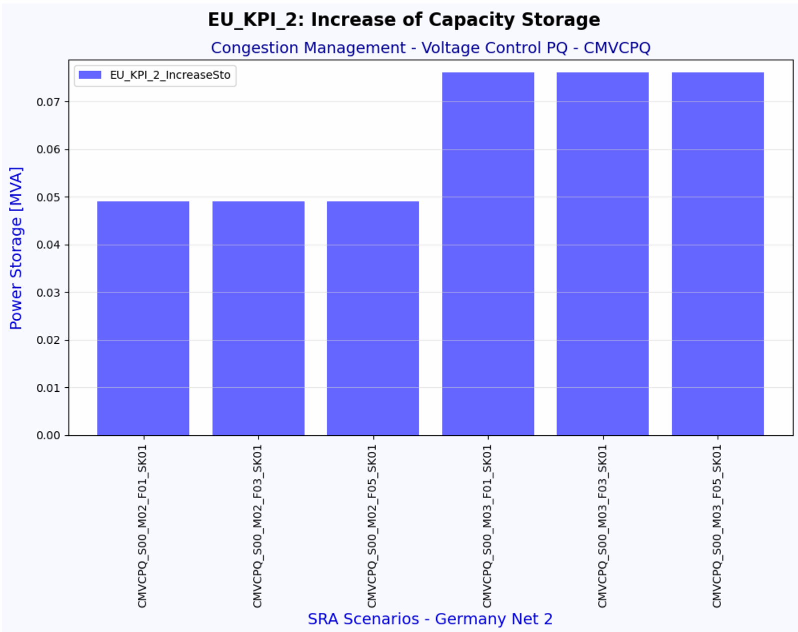
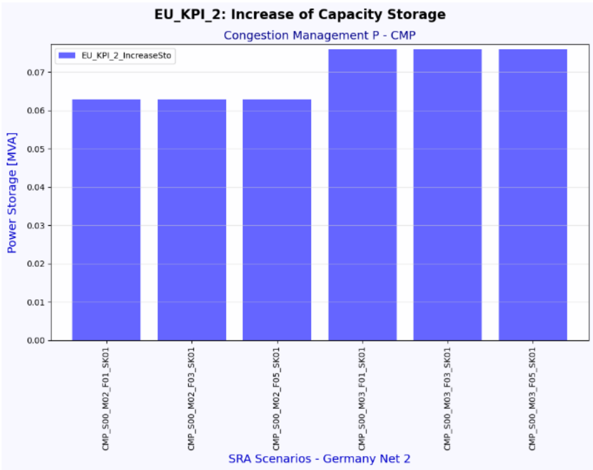
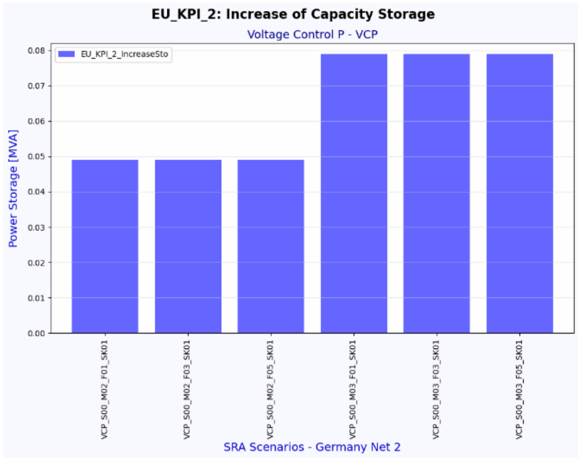


Figure 2.107 EU_KPI_2: Increased of capacity storage solution, for Congestion Management, Voltage Control using Active and Reactive Power (CMVCPQ)

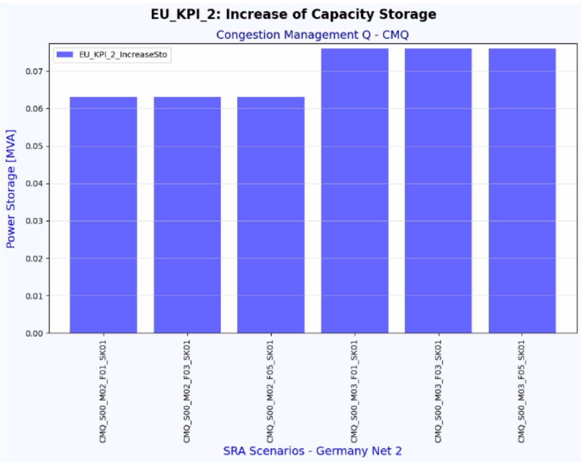
(a1)



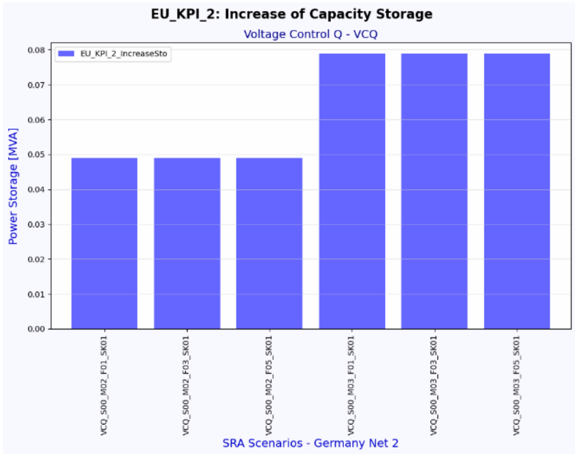
(b1)



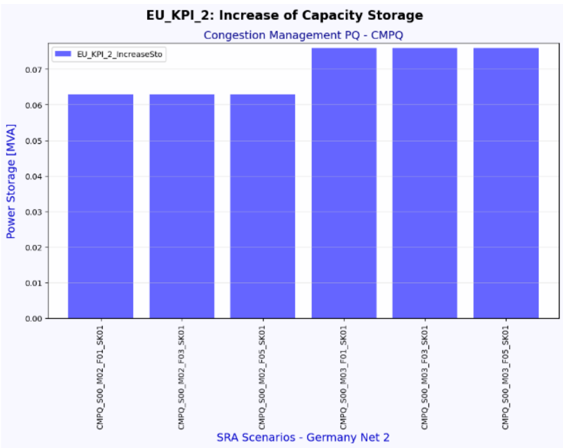
(a2)



(b2)



(a3)



(b3)

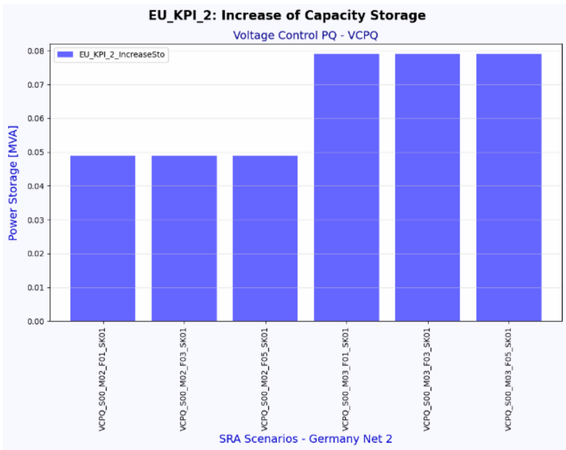


Figure 2.108 EU_KPI_2: Increased of capacity storage solution:

Congestion Management: a1) Active Power, a2) Reactive Power, a3) Active and Reactive Power. Voltage Control: b1) Active Power, b2) Reactive Power, b3) Active and Reactive Power

Figure 2.109 and Figure 2.110 display the results of all scenarios for CMVCP and CMVCQ, respectively, and taking into account the sensitivities specified in Table 2.29Table 2.9. Figure 2.111 serves as a comparative analysis, examining how the market dynamics are modified when active and reactive power are used simultaneously in the CMVCPQ market model. The different scenarios are plotted along the horizontal axis, while the vertical axes display, on the left side, the increase of Energy Storage in MVAh.

Furthermore, it is important to note that other market models have been considered to analyze their impact on the network. Figure 2.112 depicts the results obtained for this KPI when using only Congestion Management (CM) or Voltage Control (VC).

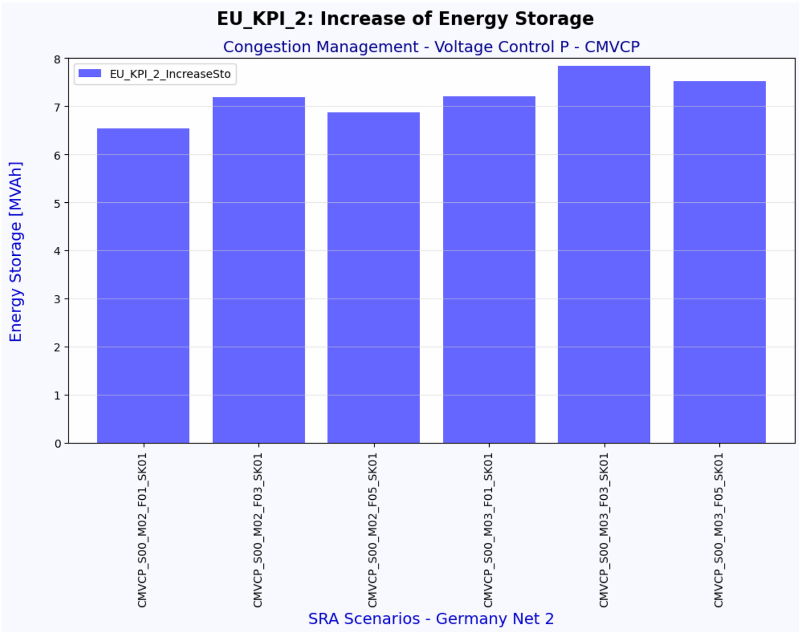


Figure 2.109 EU_KPI_2: Increased of energy storage solution for Congestion Management, Voltage Control using Active Power (CMVCP)

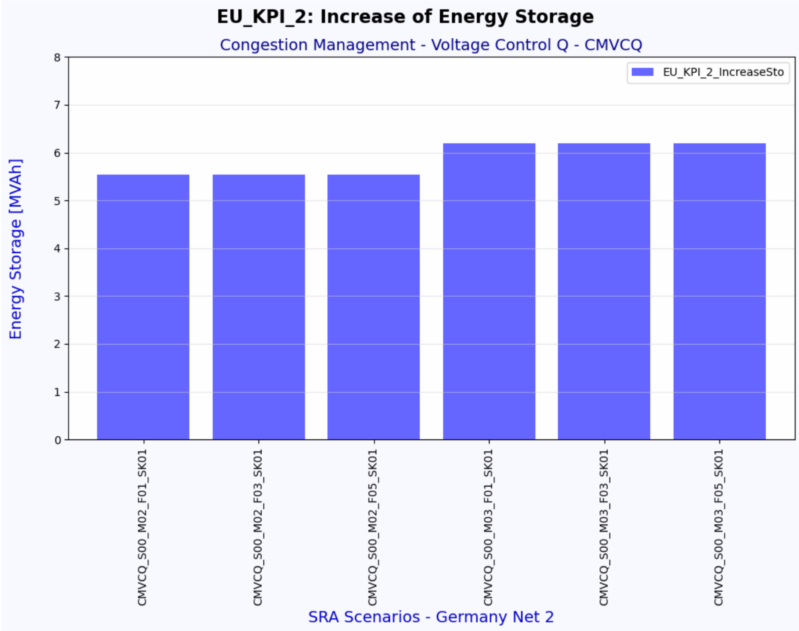


Figure 2.110 EU_KPI_2: Increased of energy storage solution for Congestion Management, Voltage Control using Reactive Power (CMVCQ)

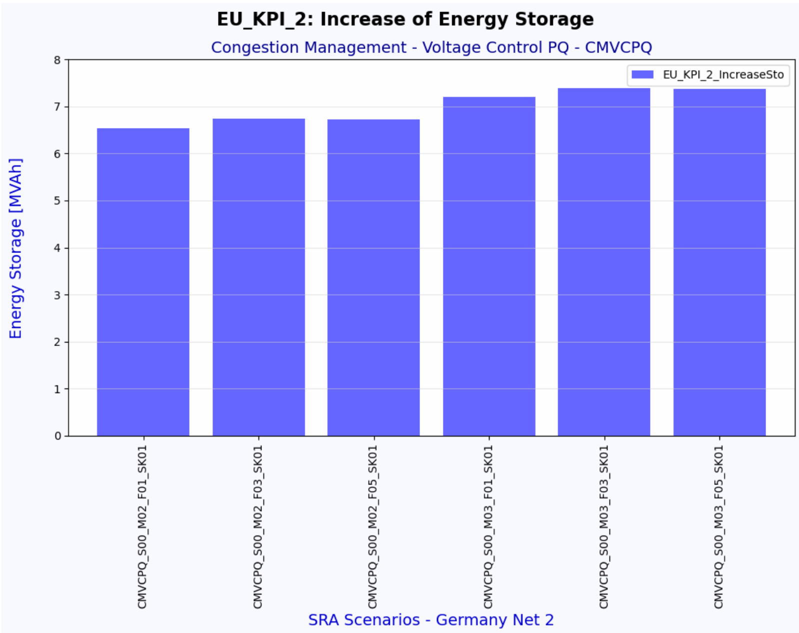
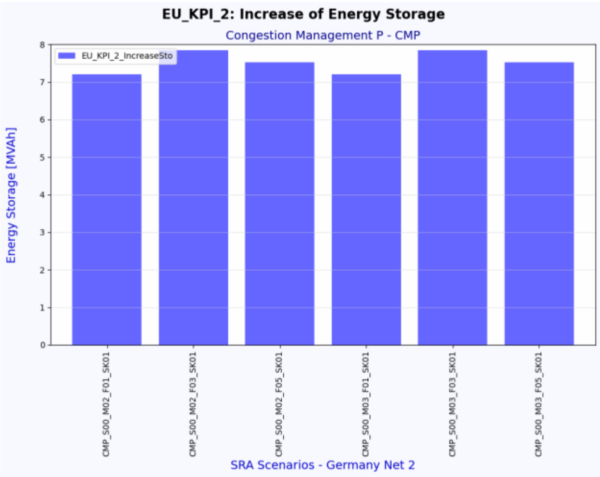
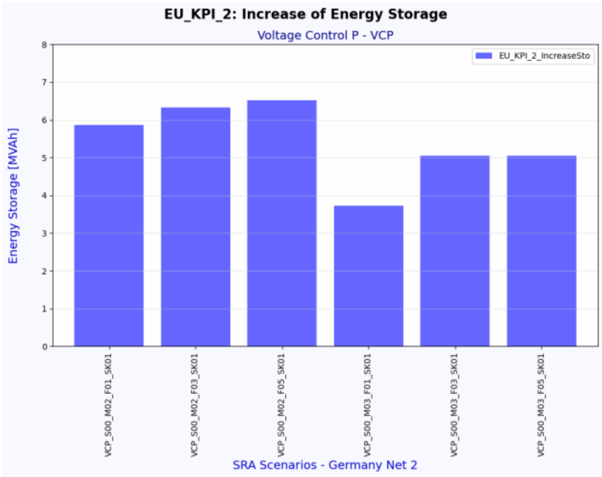


Figure 2.111 EU_KPI_2: Increased of energy storage solution for Congestion Management, Voltage Control using Active and Reactive Power (CMVCPQ)

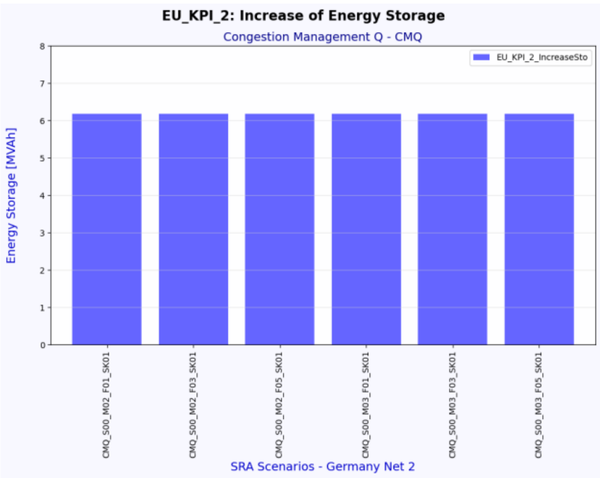
(a1)



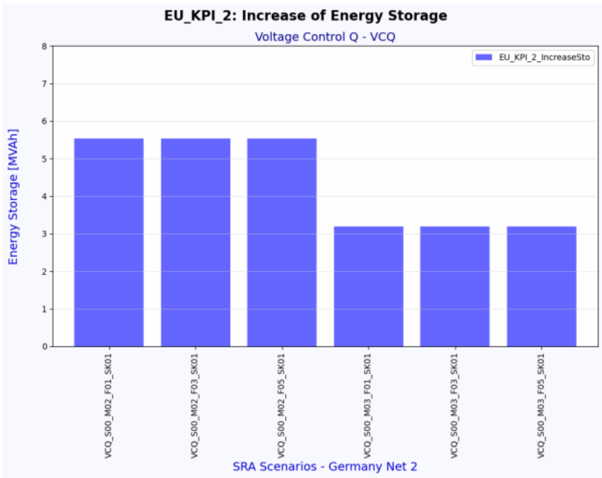
(b1)



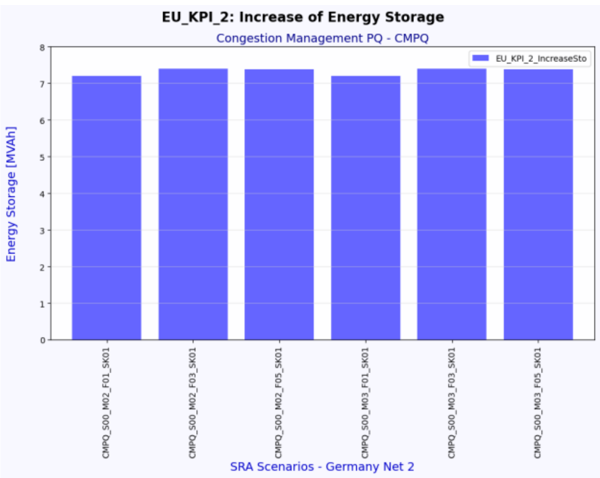
(a2)



(b2)



(a3)



(b3)

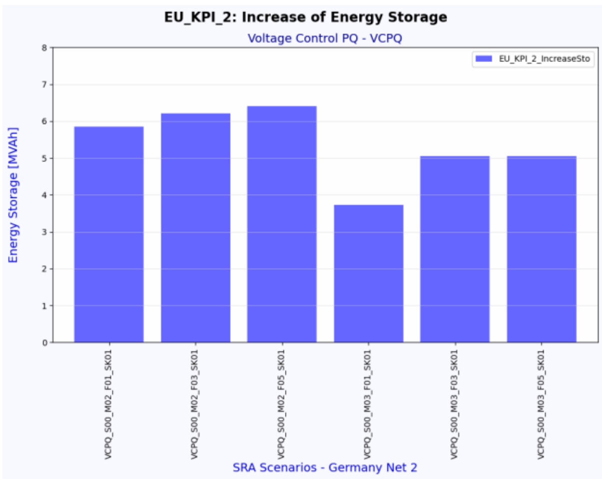


Figure 2.112 EU_KPI_2: Increased of energy storage solution:

2.5.2.4 Portuguese Demonstrator

This KPI measures the increase in Storage Solution resulting from the network improvements introduced by the market models in each scenario. For this purpose, the KPI has been divided into two components: the power term (Capacity Storage) and the energy term (Energy Storage). The power term provides a reference for the required power capacity in MVA. If the necessary equipment, such as power electronics, is available, it enables the manipulation of reactive power without consuming energy from the battery. On the other hand, the energy term offers a reference for the required storage capacity in MVAh and allows direct adjustments concerning active power utilization. Figure 2.113, Figure 2.114, Figure 2.115, and Figure 2.116 show the results for Increase of Capacity Storage, while, Figure 2.117, Figure 2.118, Figure 2.119, and Figure 2.120 show the results for Increase of Energy Storage.

Figure 2.113, and Figure 2.114 display the results of all scenarios, for CMVCP and CMVCQ, respectively, and taking into account the sensitivities specified in Section 2.4. Figure 2.115 serves as a comparative analysis, examining how the market dynamics are modified when active and reactive power are used simultaneously in the CMVCPQ market model, which presents a significant improvement in the KPI compared to the previous market models. The different scenarios are plotted along the horizontal axis, while the vertical axes display, on the left side, the increase of Capacity Storage in MVA. Furthermore, it is important to note that other market models have been considered to analyze their impact on the network. Figure 2.116 depicts the results obtained for this KPI when using only Congestion Management (CM) or Voltage Control (VC).

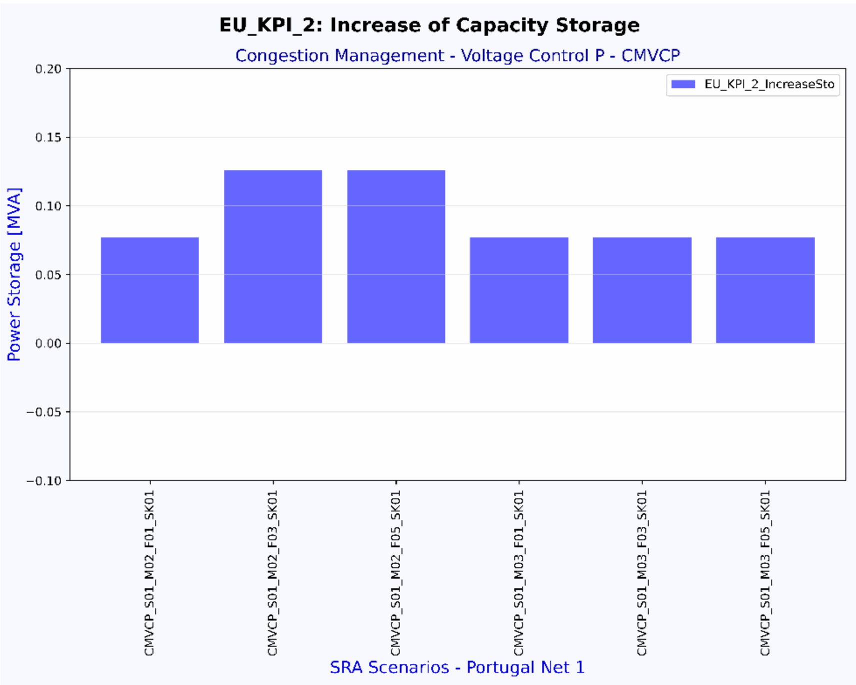


Figure 2.113 EU_KPI_2: Increased of capacity storage solution, for Congestion Management, Voltage Control using Active Power (CMVCP)

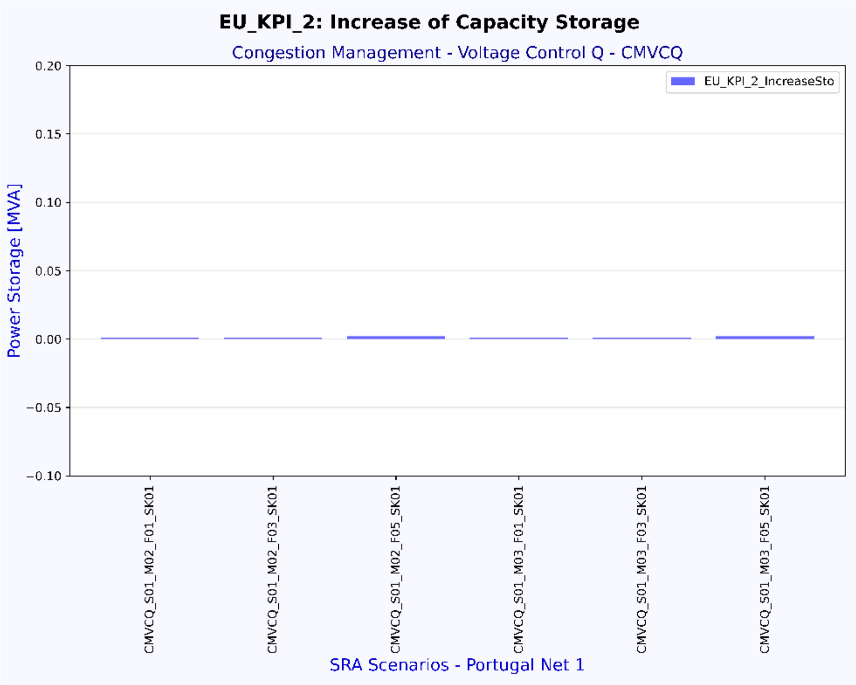


Figure 2.114 EU_KPI_2: Increased of capacity storage solution, for Congestion Management, Voltage Control using Reactive Power (CMVCQ)

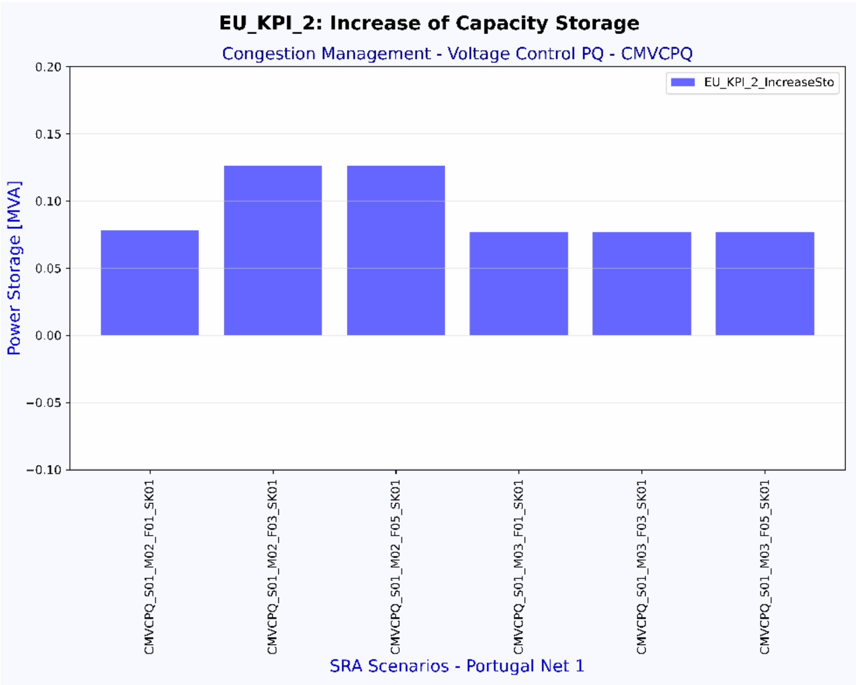
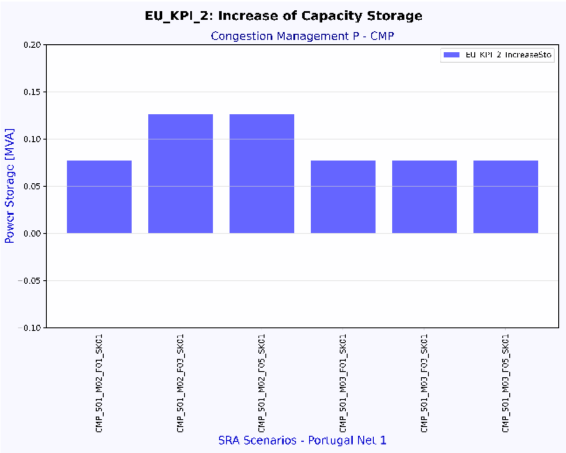
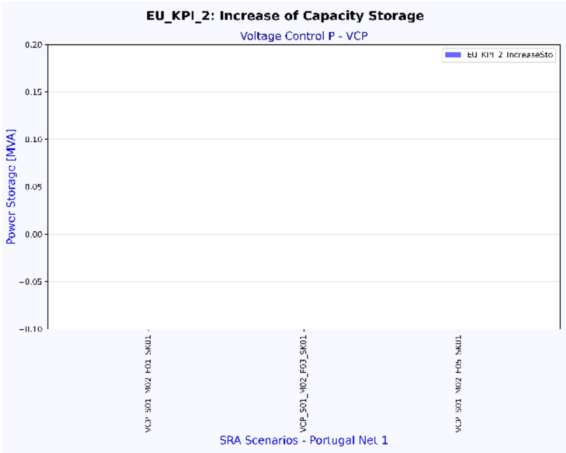


Figure 2.115 EU_KPI_2: Increased of capacity storage solution, for Congestion Management, Voltage Control using Active and Reactive Power (CMVCPQ)

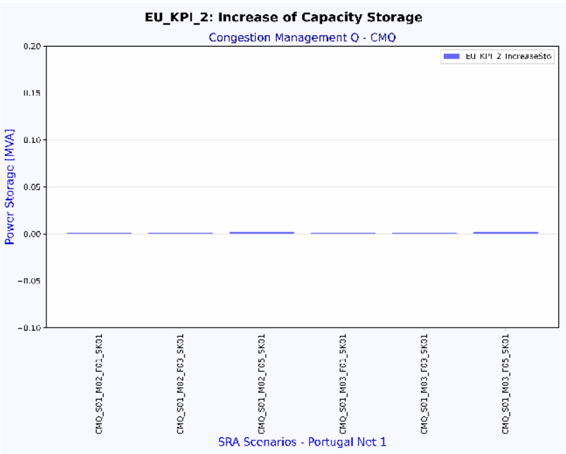
(a1)



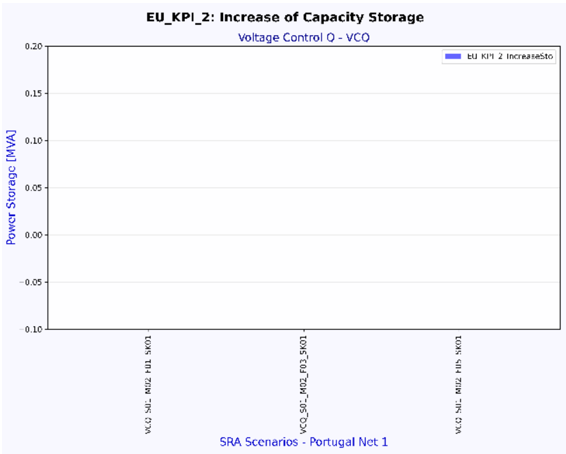
(b1)



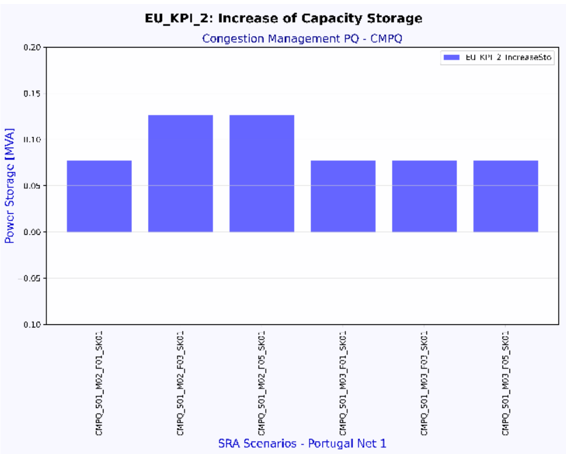
(a2)



(b2)



(a3)



(b3)

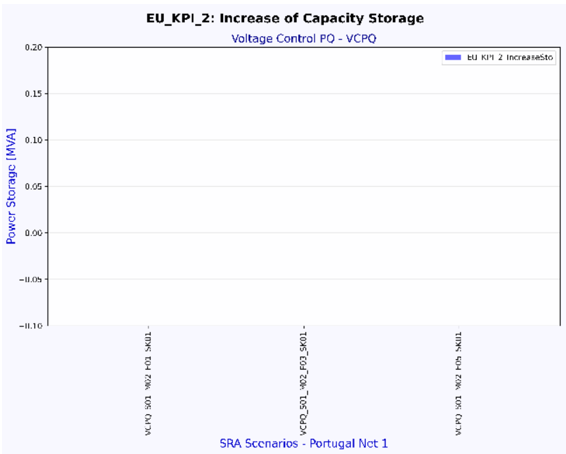


Figure 2.116 EU_KPI_2: Increased of capacity storage solution:

Congestion Management: a1) Active Power, a2) Reactive Power, a3) Active and Reactive Power. Voltage Control: b1) Active Power, b2) Reactive Power, b3) Active and Reactive Power

Figure 2.117, and Figure 2.118 display the results of all scenarios, for CMVCP and CMVCQ, respectively, and taking into account the sensitivities specified in Section 2.4. Figure 2.119 serves as a comparative analysis, examining how the market dynamics are modified when active and reactive power are used simultaneously in the CMVCPQ market model. The different scenarios are plotted along the horizontal axis, while the vertical axes display, on the left side, the increase of Energy Storage in MVAh.

Furthermore, it is important to note that other market models have been considered to analyze their impact on the network. Figure 2.120 depicts the results obtained for this KPI when using only Congestion Management (CM) or Voltage Control (VC).

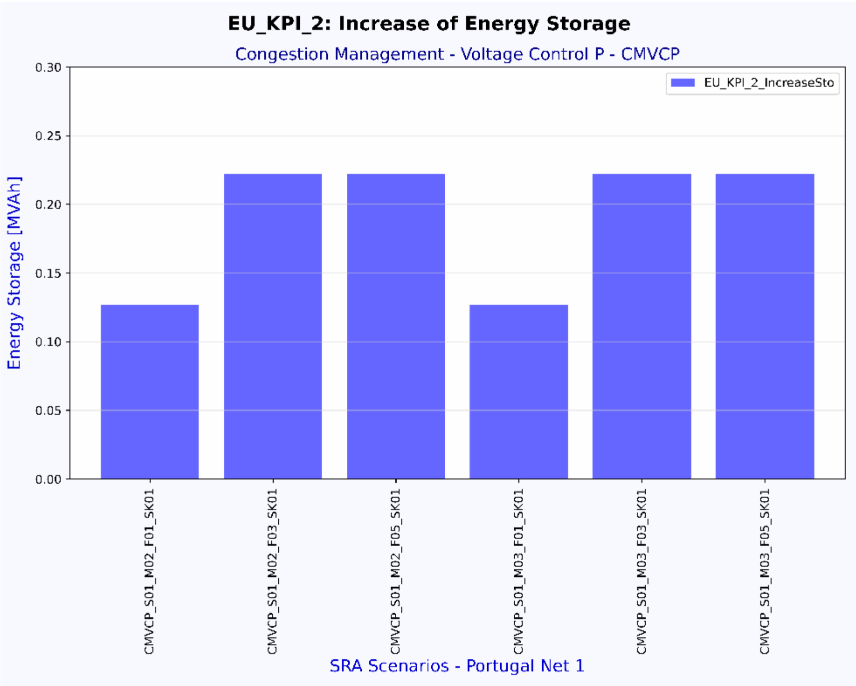


Figure 2.117 EU_KPI_2: Increased of energy storage solution for Congestion Management, Voltage Control using Active Power (CMVCP)

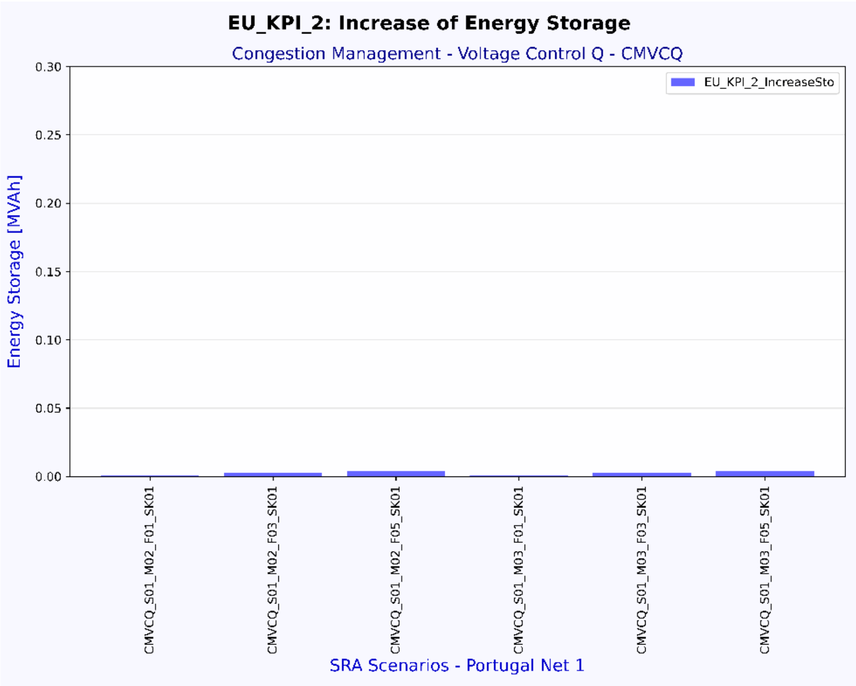


Figure 2.118 EU_KPI_2: Increased of energy storage solution, for Congestion Management, Voltage Control using Reactive Power (CMVCQ)

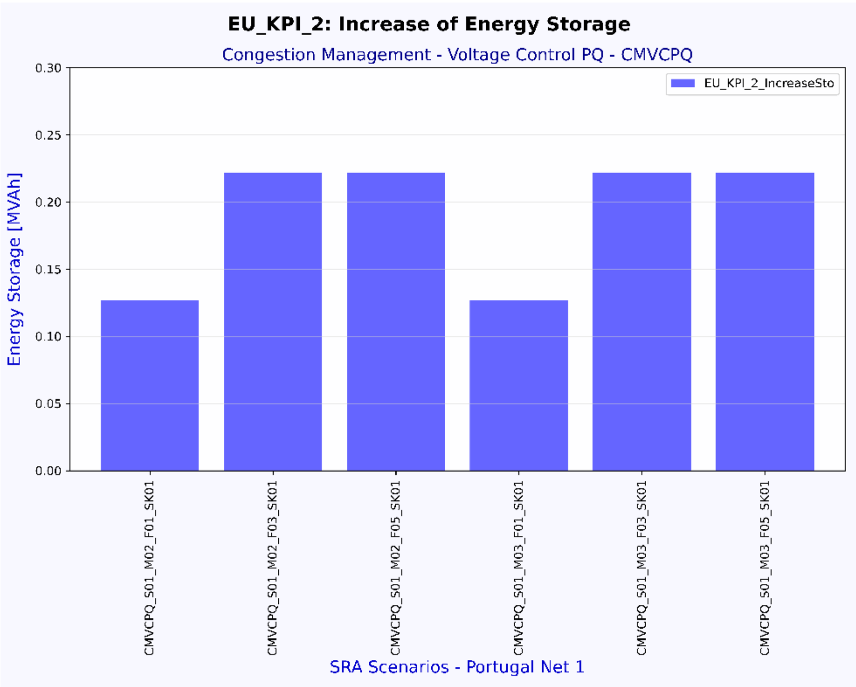
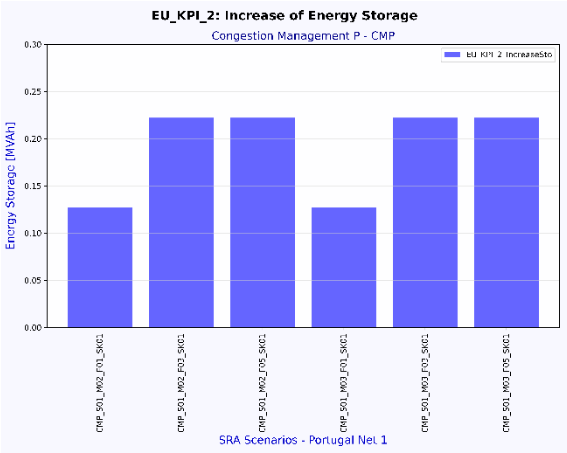
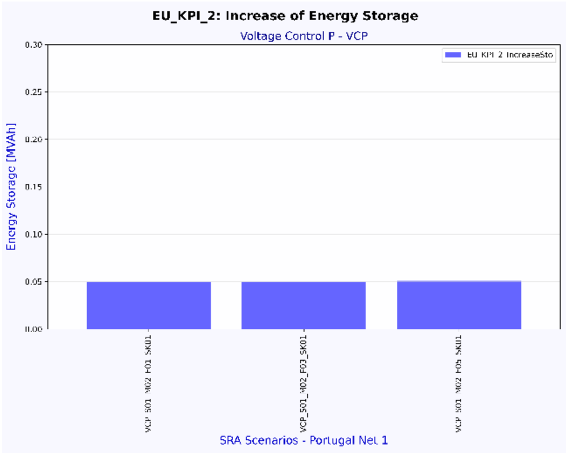


Figure 2.119 EU_KPI_2: Increased of energy storage solution, for Congestion Management, Voltage Control using Active and Reactive Power (CMVCPQ)

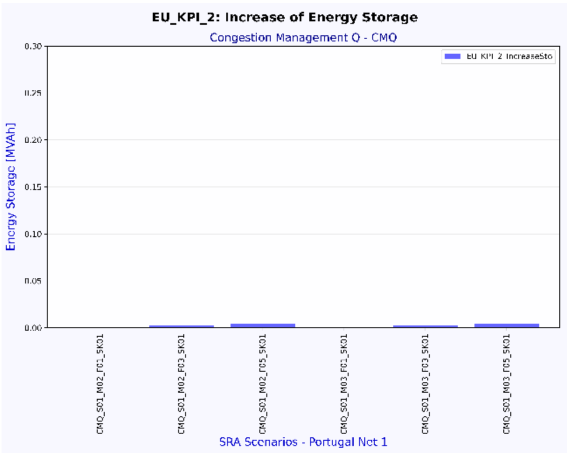
(a1)



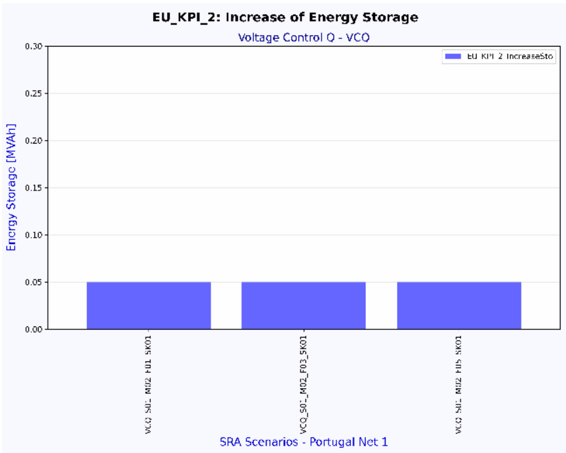
(b1)



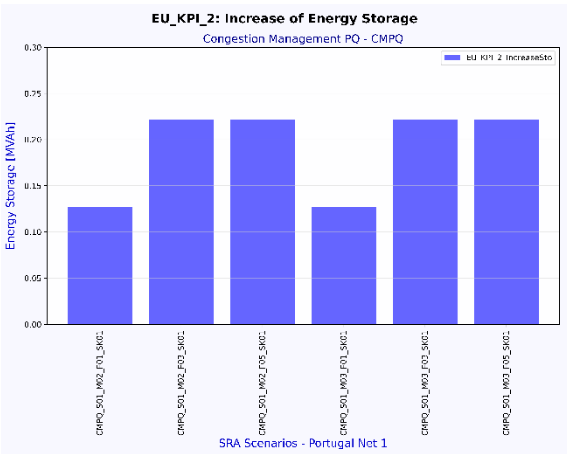
(a2)



(b2)



(a3)



(b3)

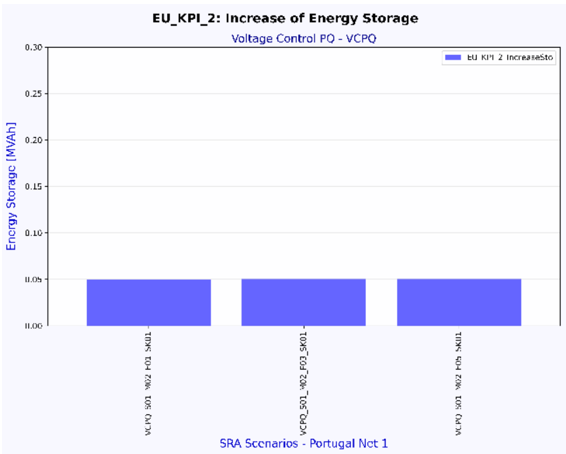


Figure 2.120 EU_KPI_2: Increased of energy storage solution:

Congestion Management: a1) Active Power, a2) Reactive Power, a3) Active and Reactive Power. Voltage Control: b1) Active Power, b2) Reactive Power, b3) Active and Reactive Power

3. Qualitative SRA

3.1 Aims and scope of the qualitative SRA

Scalability and replicability can be heavily influenced by non-technical boundary conditions related to regulation, economic, or stakeholder-related factors. Therefore, the technical analysis is complemented with a qualitative assessment of these non-technical boundary conditions.

A preliminary mapping of relevant regulatory topics and stakeholders was presented in EUniversal deliverable D10.2 SRA Methodology as can be observed in Table 3.1 where the main regulatory topic for the DSO, the FSP and the flexibility market operator are outlined. Figure 3.1 presents the methodology and previous work in the project that has informed the discussions presented in this chapter. Based on the previous analysis done, this chapter presents the answers to open questions faced by stakeholders and regulators. The assessment in this chapter is based on topic relevance within each given context, therefore the preliminary mapping first presented is indicative but does not dictate the structure of the chapter.

This chapter is divided into three parts, first we present the main open regulatory questions in congestion management in European Distribution Grids. Second, we present our conclusions regarding the replicability of the flexibility business model. Third, we conclude with regulatory recommendations to enable the growth of flexibility markets in Europe.

Table 3.1 Preliminary mapping of relevant regulatory topics and stakeholders

Topic	Main Stakeholder		
	DSO	FSP	MO
Distribution network tariffs	X	X	X
Connection agreements	X	X	X
Flexibility services and markets	X	X	X
Balancing market design	X	X	X
Redispatch market design	X	X	X
Regulatory sandboxes	X	X	X
DSO incentives for innovation	X		
DSO remuneration	X		
Grid investment plans	X		
Smart meter infrastructure	X		
Grid data sharing	X	X	X
Customer data sharing and GDPR	X	X	X
Aggregation		X	
Energy communities		X	
Responsibilities for market operators			X

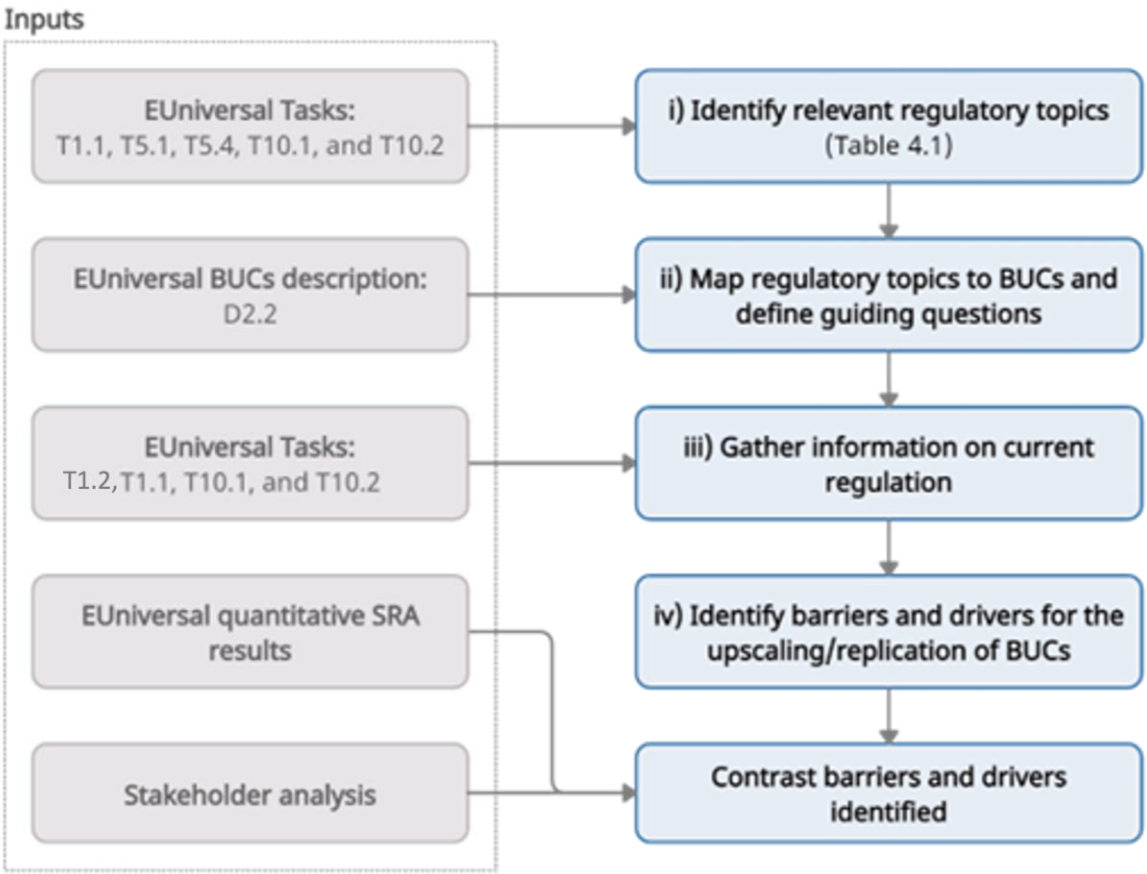


Figure 3.1: Regulatory analysis methodology and scope

3.2 Open questions in Congestion in European Distribution grids: from 'Fit and Forget' to 'Flex or Regret'

This section presents a discussion regarding the main open questions regarding congestion management in European Distribution grids:

- *Do we plan to have more congestion in distribution grids, or do we need better planning to avoid congestion?*
- *How do DSOs procure grid services to solve congestion, and what are the main differences?*
- *Does incentive regulation need to be enhanced to make sure DSOs consider flexibility as an alternative to investments?*
- *In what situation will we use which approach to source flexibility?*
- *How do we ensure coordination between TSOs and DSOs?*

To describe the open questions in a comprehensive and clear way, the research performed in the context of this deliverable is summarized in the following pages and made fully available online as a publication [23]. [19]

- ***Do we plan to have more congestion in distribution grids, or do we need better planning to avoid congestion?***

For more than a decade, European transmission investment plans have been publicly discussed. These national plans are developed with standardized methodologies and coordinated by a pan-European strategy. This exercise, led by ENTSO-E, the European Network of TSOs for electricity, is referred to as the Ten-Year Network Development Plan. The plan, which is updated and improved every other year, has been an impressive achievement of harmonization and collaboration across many countries.

In the first two decades of electricity market reforms, congestion in distribution grids has not been an issue. But recently, it became evident that distribution grids can turn into a bottleneck for the functioning of the European electricity market and the transition towards a more sustainable energy system. Article 32 of Electricity Directive 2019/944 of the EU Clean Energy Package [24] introduced several new regulations for distribution network planning. The legislation uses the terminology "network investment plans for distribution systems," but some are already talking about Ten-Year Network Development Plans for distribution. DSOs have promoted the EU DSO Entity, aimed at replicating the role of ENTSO-E, to develop a new methodology for the future investment plans of distribution grids that all DSOs will apply. In the meantime, different approaches to designing these network investment plans are emerging.

On the one hand, DSOs gathered via their industry associations and asked consultants to produce a first European plan as a dry-run. On the other hand, DSOs have already published the first version of their local plans to comply with the new regulations of the Clean Energy Package. For example, the first European plan was developed by Eurelectric, Monitor Deloitte, and E.DSO. The study argues that evening peaks of households will drive congestion and investments in distribution grids and illustrates this with the European version of the duck curve, reflecting the impact of solar production mainly around noon. Figure 3.2 taken from this study, argues that investments in the next 10 years will need to increase annually between 50 and 70% (from an average of 23 billion per year to between 34 and 39 billion per year). Important assumptions for such a plan are the renewable energy objectives and the ambition to electrify transport and heating. Even though most European countries have clear national targets, inferring the future impact on local distribution grids is not always obvious. Another key assumption is the level of flexibility that will be available, which will depend on the incentives in place to manage peaks and the resulting response from end users. The first European plan treats flexibility as an assumption, while European legislation asks DSOs to consider the trade-off between flexibility and expansion of the network in their upcoming network development plans.

[19] This section focuses on congestion management, but voltage control is also an acknowledged issue in distribution networks (and will be increasingly important in the context of DSO-TSO coordination).

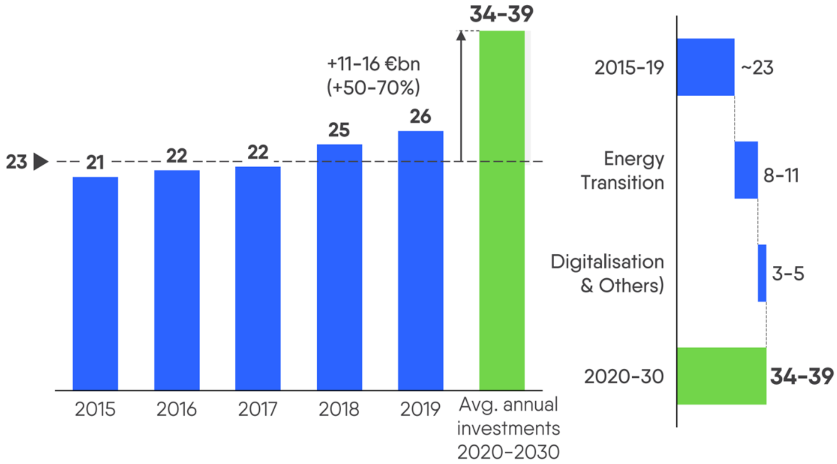


Figure 3.2: Expected increase in annual distribution network investments in Europe and its main drivers. Source: [25]

There is not yet a consensus on the actual potential of flexibility as an alternative to distribution grid investments. Some argue that cost-reflective distribution network tariffs would bring enough incentives for grid users to reduce their peaks. We believe there is a potential for DSOs to do more than provide cost-reflective signals via their network tariffs. One reason to defend the need to explicitly procure flexibility, in addition to relying only on the energy component of tariffs, is that tariffs will always depend on the grid users' voluntary response and be imperfect as they compromise between cost-reflectiveness and other principles, such as fairness and simplicity. Another reason is that investment planning under uncertainty can result in unexpected congestion.

The European countries that currently experience congestion in distribution grids indeed did not plan for it, but they still have to deal with it. The experience has shown that DSOs cannot simply stop all requests to connect to distribution grids; they are subject to significant pressure to overbook and manage the congestion resulting from this overbooking. An additional concern is that grid users could start to create congestion, anticipating that they can get paid to solve it (i.e., inc-dec gaming). Gaming is a valid concern limiting the potential of market-based flexibility, but we believe it will not apply equally in all situations. When and how DSOs will contract flexibility also plays a role, which is what we will discuss next.

- ***How do DSOs procure grid services to solve congestion, and what are the main differences?***

Many DSOs in Europe have set up demonstration projects to test flexibility services to manage (potential) congestion in their grids. DSOs with a lot of congestion in their networks evolved from demonstration projects to full-scale flexibility markets. Some DSOs, such as Enedis and ENEL, have developed their own platforms to tender flexibility services, but market platforms owned and operated by third-party companies also entered into this space. All initiatives started in countries that were among the first to experience congestion in distribution grids: Norway and Germany for NODES, the UK for Piclo Flex, and the Netherlands for GOPACS.

A fundamental difference in the approaches of the UK, the Netherlands and Germany exists. In the UK, the DSOs really plan for flexibility. They make the trade-off between distribution grid expansions and procuring flexibility. UKPN, for example, recently committed in their RIIO-ED2 Business Plan 2023- 2028 to 410 million pounds of deferred load-related investments through the use of low-voltage flexibility. They estimated the cost of the flexibility services based on their experience with flexibility tenders. The DSOs in the Netherlands did not plan to use flexibility. They are forced to overbook the grids as they cannot follow the demand for grid connections and then have to procure flexibility to solve the resulting congestion in their grids. This situation is not the result of a cost-benefit analysis.

The DSOs in Germany are also in a different situation. They have also been overbooking their grids because there was a bigger demand for grid connection than they could offer, leading to high curtailment rates in certain areas. However, after controlling the most severe capacity issues with network investments, German DSOs can do a cost-benefit analysis to compare the cost of curtailment with the investment cost to expand their grids. In more detail, they can consider a curtailment of 3% of the annual output of each connection point in their network planning. In this context, buying flexibility services can be an alternative to compensating grid users for curtailing them. In other words, the German situation nicely illustrates how we can avoid DSOs being at the mercy of flexible service providers to solve congestion in distribution grids (the biggest worry of some sceptics).

- ***Does incentive regulation need to be enhanced to make sure DSOs consider flexibility as an alternative to investments?***

Flexibility services are operating expenditures (OPEX), and DSOs typically have efficiency benchmarks for OPEX with rewards if they outperform their OPEX baseline and penalties if they underperform. Distribution grid investments, however, are treated differently as capital expenditures (CAPEX). Once approved, CAPEX enters into the regulated asset base, on which the DSO receives a regulated rate of return. When DSOs use flexibility as an alternative to distribution grid investments, OPEX (cost of flexibility services) increases and CAPEX (cost of investments) decreases, negatively impacting their efficiency benchmarks and return on investments.

The regulatory authority in the UK, Ofgem, has been one of the first to address this financial disincentive by introducing what they refer to as the TOTEX approach. It implies that a fixed share of the total expenditures (OPEX and CAPEX) can enter into the regulated asset base, which gives DSOs incentives to consider flexibility as an alternative to grid investments. Today, there is an ongoing discussion on whether to address this disincentive with regulatory measures. The most advanced incentive regulation schemes developed to address this issue have reached an inadvisable level of complexity. Considering that DSOs are anyway under pressure to keep their network tariffs under control, maybe the current push for more transparent network investment plans can be sufficient to compensate for the financial disincentive.

- ***In what situation will we use which approach to source flexibility?***

While the main focus of this article is on flexibility markets, there are also other ways to source flexibility. Generally, the provision of flexibility can be mandatory or voluntary, and flexibility contracts can be short- or long-termed. Table 3.2 illustrates both approaches by mapping different flexibility tools on these two dimensions. While each approach has its opportunities and disadvantages, the magnitude of these effects still needs to be determined. As a result, DSOs are examining different ways to contract flexibility in their networks. For example, the Dutch DSO Liander currently considers four congestion management alternatives to connect new grid users in congested network areas. Two types of short-term flexibility markets are tested using the GOPACS platform characterized by voluntary or mandatory participation of this new grid user in the market. Besides that, new grid users can enter two kinds of long-term connection agreements, with and without day-ahead curtailment announcements by the system operator.

It will be interesting to learn more from theory and practice about the optimal approach to source flexibility and the interdependence of this choice on local network characteristics such as the number of available flexible resources, grid topology (rural, urban,..), voltage level (LV, MV,..) and congestion cause (renewables, EVs, data centres,..). Also, it will be important to understand better the pros and cons of combining different flexibility tools. While incompatibilities between the different approaches might exist, we also see opportunities in combining them, for instance, long-term flexibility contracts (voluntary or mandatory) with shorter-term flexibility markets.

Table 3.2 Illustration of the two approaches to source flexibility using existing flexibility tools

	Mandatory	Voluntary
Short-term		• Flexibility markets
Long-term	• Default non-firm connection contract • Grid connection requirements	• Flexibility markets • Choosing between firm and non-firm connection agreement.

- ***How do we ensure coordination between TSOs and DSOs?***

We have discussed the challenges and opportunities of procuring flexibility from a DSO perspective. However, the DSO's activation of flexibility might also impact other energy stakeholders, such as the TSO. There are at least two interactions between TSOs and DSOs to consider. First, TSOs and DSOs might want to access the same flexible resources for different grid services, such as congestion management and balancing. This competitive interaction between system operators might create a need for cooperation or sequence in selecting flexible units. Second, TSOs and DSOs might impact each other's network when activating flexible resources for their own purposes. When the activation of flexibility moves closer to real-time, there might be a need for coordination or validation mechanisms between the system operators to avoid network issues.

Many stakeholders and academics already recognized the importance of TSO-DSO coordination, which led to the development of different coordination schemes for the TSO's balancing and the TSO's and DSO's congestion management services. However, translating these coordination schemes into practice is often difficult due to the complexity of the problem and the required information sharing between the stakeholders. Therefore, new regulations to manage the described interactions between system operators might arise in the meantime. An example is the European System Operation Guideline that allows DSOs to refuse the participation of flexible resources to the TSO balancing market based on technical reasons. It is only to see how these rules and coordination schemes will evolve in the coming years.

Key Takeaways:

1. DSOs in European countries, such as Germany and the Netherlands, increasingly face congestion in their distribution networks due to the connection of renewables, electric vehicles, and new loads like data centres. Heatmaps or hosting capacity maps are typically used by DSOs to report their congestion issues to grid users, and different practices exist.
2. Current practices on distribution network plans show the need for increased grid investments in the coming year to control congestion levels and recognize the opportunity for flexibility to contain these investment costs. However, there is not yet a consensus on the actual potential of flexibility as an alternative to distribution grid investments.
3. Third-party market platforms such as Piclo-Flex, GOPACS and NODES are tapping into this opportunity for flexibility and are quickly growing over the years. These flexibility markets are used by DSOs for different reasons (e.g., to trade flexibility proactively or out of necessity) and have developed diverse types of products, time-frames, and interactions with existing markets and system operators.
4. Open issues regarding congestion management in distribution grids include the financial incentives for DSOs to consider flexibility as an alternative to grid investments, the best approach for DSOs to contract flexibility regarding local network characteristics and the coordination between the DSO and other stakeholders such as the TSO.
5. The procurement of flexibility for voltage control, as a separate product, will also become important for distribution grids.

In other words, when fit-and-forget is not an option anymore, we will have DSOs that proactively engage in flexibility and DSOs that might regret they did not, hence the title.

3.3 Business model Replicability

The business model canvas of the EUniversal demos was proposed in Deliverable 10.1 [26], 'Business model canvas and comparison of CBA methodologies.' In this section we explore three main concepts[20]:

- Which parts of the flexibility business model are local and must be custom built every time a flexibility market will be implemented
- Which parts of the flexibility business model can be replicated in future projects.
- The link to flexibility market tools for either congestion management or voltage control.

[20] The findings are based on conceptual discussion with project partners during a workshop in Halle, Germany in October 2022 and through follow-up bilateral calls.

It must be noted that Figure 3.3 groups all possible options in the same canvas, while not all of them apply for every demo:

- Congestion management & voltage control with market based active and reactive power flexibility (Portugal & Germany demos)
- Congestion management using permissible line capacity based on dynamic line rating system such that wind producers can buy flexibility from the DSO in a market-based way and generate above their connection agreement. (Poland demo)
- Voltage Control with the use of flex station solutions under a bilateral contract (Poland demo).

Local elements are those that are specific to a location, they must be built or negotiated in a customized way every time a new flexibility market will be opened. The main concepts that are entirely local are the key partners, key resources, customer relationships and some key activities. Key partners such as market operators and technology providers can provide services across different countries. Their presence in a given market is determined by their commercial opportunity in a given place. In this aspect, they can be both local or international, but they must have the ability to operate in each different market. Key resources are those that enable the exploitation of flexibility itself, they refer to network elements, network topology smart grid infrastructure and/or flexible resources owned by the DSO directly. Customer relationships are always local as flexibility must be procured in the place where it is needed. Customers must be willing to participate in a flexibility market. Depending on their profile, a certain number of customers is necessary per location to really provide flexibility that will be significant for the system. Engaging enough customers per area can be a local challenge in replicating flexibility markets. It is a role that can be taken on by either the DSO directly, the market operator or an independent aggregator. Key activities are those that enable the value proposition of the business model. For the DSO local tasks that must be customized include identifying their flexibility needs, grid access, system operation and technical validation.

Replicable or non-local elements are those that can conceptually be translated from one flexibility market to another in a different location. The implementation of a new flexibility market will always be done on location, but the reasoning behind the business model, the standards, and some of the tools used can be carried from one location to another. While the specific implementation options depend on local regulation and needs, the same reasoning can be applied for some elements. We find that the value proposition, cost structure, channels, revenue streams, technology and market provider, and customer segmentation elements of the business model can be conceptually replicated from one market to another. The value proposition, in terms of value created by flexibility market for aggregators and producers is replicable. The UMEI developed as part of EUniversal provides a standard toolset with which DSOs, flexibility service providers and market operators can communicate to perform flexibility service provision. The UMEI provides a standard for data handling, communication, and flexibility operations. The cost structure and revenue streams concepts remain the same across different flexibility markets, although their implementation will be different depending on the local regulation. The methodologies used to calculate costs and revenues can be carried across from one market to another depending on the choice of tools.

Different tools can be used for **acquiring grid services for congestion management and voltage control**: flexible connection and access agreements, dynamic network tariffs, local market, bilateral contracts, cost-based flexibility, and obligations. These tools define the specifics of the key activities and customer relationships elements of the business model. Table 5.2 on page 110 of EUniversal D5.1 highlights the applicability of these tools for congestion management and voltage control. In summary, all tools can be suitable for congestion management, while only bilateral contracts and obligations have been found to be highly suitable for voltage control. In terms of replicability and scalability, we estimate that conceptually bilateral contracts and obligations are not local. In terms of implementation, the local regulation will determine whether and how these two tools can be used. Obligations can only be imposed under a regulatory framework that determines threshold conditions. Specifically speaking about voltage control, in the Polish demo, for example, the EUniversal partners determined that both congestion management and voltage control with market based active and reactive power flexibility could be replicable. The inverter needed to measure voltage could be replicable but needs to be adapted to the local network configuration, but the local flexibility substation was built specifically for their network and they don't consider it to be local. The idea could be taken up by other DSO networks but there is a significant effort needed to build it up to local specifications.

Table 5-2. Applicability of the mechanisms for acquiring grid services

	Flexible connection and access agreements	Dynamic network tariffs	Local market	Bilateral contract	Cost-based	Obligation
Congestion management (Active power)						
Voltage control (Reactive power)						

Legend:

Suitability	High	Weak	Low

In summary, we can observe that opening a flexibility market in a new location carries challenges due to the local nature of flexibility needs, network topology, regulation and resource availability. Nevertheless, here we conclude that the flexibility business model has important elements that can be conceptually applied across different locations. Specifically, the value proposition, communication channels and standards, and the logic behind costs and revenues can be exported to new implementations.

Key Partners	Key Activities	Value Propositions	Customer Relationships	Customer Segments
• Market platform provider and operator: NODES & N-SIDE • Technology and tools providers: INESC	• Operating, maintaining a secure and reliable system • Ensure grid access • Grid optimization	Value for flexibility provider • Financial revenues	• Previously existing flexibility participants.	• Residential, commercial, industrial customers and the service sector can

<table>
<tr>
<td rowspan="2">TEC, VITO, Centrica, KUL, N-side, IEN, Miktronika
Local regulators
• Participating DSOs</td>
<td>• Assess impact flexibility and balancing
• Provide required data
• Identify flexibility needs
• Technical validation
• Data handling</td>
<td rowspan="2">• Revenue stacking via UMEI

Value for wind producers (Polish demo):
• Produce more than contracted in connection agreement.</td>
<td>• Customers attracted by key partners or DSO.</td>
<td rowspan="2">become flexibility providers if they prequalify.
• Resource providers (MV)
• Resource aggregators (LV)</td>
</tr>
<tr>
<td>Key Resources

• Distribution network: LV/MV network
• Smart grid infrastructure
• Flex station
• DSO owns flexible resources</td>
<td>Channels

• UMEI with communication standards
• Connection agreements
• Bilateral Contracts</td>
</tr>
<tr>
<td colspan="2">Cost Structure
• Remuneration cost of flexibility (availability [€/MW/h] [€/MVar/h] or
• Remuneration of flexibility for activation [€/MW] [€/Mvar])</td>
<td colspan="3">Revenue Streams
The positive impact of services: solutions to specific grid issues, delay in network investments
• Congestion management & voltage control (active and reactive power)
• Better monitoring, operation, maintenance, and planning of the grid, both in the short-term and long-term
• Producers avoid curtailment due to network congestion.
• Possible avoided grid investment.</td>
</tr>
</table>

Replicable elements are highlighted

Figure 3.3: Generic Business Model Canvas for congestion management and voltage control in the EUniversal demos

3.4 Enablers: Regulatory Recommendations for congestion management and voltage control in distribution grids

This section describes three regulatory recommendations from Work Package 10 of the EUniversal H2020 project. These recommendations also summarize our insights on congestion management in distribution grids published in the Oxford Energy Forum[21] and the IEEE Power and Energy Magazine[22].

Recommendation 1: We encourage the use of congestion and voltage heatmaps and the development of guidelines on the trade-off between flexibility and grid investments to advance the planning of distribution grids

As distribution grids are one of the key enablers in the transition towards a more sustainable energy system, appropriate planning of these grids becomes increasingly important. We identified two open issues when advancing distribution network plans: the detailed representation of the grid and the trade-off between flexibility and grid

[21] Meeus, L., Beckstedde, E., Nouicer, A. (2022). Towards a regulatory framework for the use of flexibility in distribution grids. Oxford Energy Forum. Issue 134, The Future of Energy Networks in a Decarbonized World [35].

[22] Meeus, L., Beckstedde, E. (2023). Congestion management in distribution grids. IEEE Power & Energy Magazine. Issue on Regulatory & Market Tools and Solutions to Empower End-Users towards Power Systems Decarbonization [23].

investments. First, moving toward a more detailed representation of the grid requires a digital network model and raises security concerns for DSOs when sharing network plans with stakeholders. We identify network congestion heatmaps as an interesting tool to deal with the latter concern and create a balance between security issues, transparency and engagement of grid users.[23] We must take into account that the issue of network observability, specifically for LV networks, is limited for DSOs, and it might still represent high investment costs for DSOs. Second, developing a robust methodology to consider the trade-off between flexibility and grid investments in network planning is often challenging for DSOs, even though many have set up demo projects to test flexibility as a (temporary) alternative to grid investments.[24] Here, we encourage sharing guidelines and best practices to further develop this trade-off in distribution network planning.

Recommendation 2: We invite everyone to keep an open mind regarding the way DSOs will contract flexibility and gain insights about the local interactions at play

Even if we improve distribution network plans, investment planning under uncertainty can still result in unexpected congestion with which DSOs will have to deal. Here, one of the main concerns is that grid users could start to create congestion at distribution level, anticipating that they can get paid to solve it (i.e., inc-dec gaming). In our research, we find that this is a valid concern for which regulatory remedies might be needed.[25] However, we believe this concern will not apply equally in all situations: when and how DSOs contract flexibility will also play a role. Generally, we find that the provision of flexibility can be mandatory or voluntary, and flexibility contracts can be short or long-term. While research projects such as EUniversal allow us to gain knowledge of the optimal way to contract flexibility, the interdependence of this choice on local contexts (e.g., available flexible resources, grid topology, voltage level, and congestion cause) is still unclear. Also the effect of combining different approaches is not always certain.[26] Therefore, we invite everyone to keep an open mind regarding the way DSOs will contract flexibility and gain insights about the local interactions at play.

Recommendation 3: We promote the design of open, tangible and up-to-date legal frameworks for regulatory sandboxes to foster innovation in the use of flexibility in distribution grids

[23] The findings are based on interviews and discussions with 11 European DSOs. A complete evaluation of distribution network planning methodologies in Europe can be found in EUniversal Deliverable 10.1 [26]: Business model canvas and comparison of CBA methodologies. Examples of network congestion heatmaps can be found in the same deliverable and our forthcoming article in the IEEE Power & Energy Magazine.

[24] The results are based on the business model canvas analysis of the EUniversal demos and were confirmed during the evaluation of distribution network planning methodologies (see footnote 4). A detailed analysis can be found in EUniversal Deliverable 10.1 [26]: Business model canvas and comparison of CBA methodologies. More information on how this trade-off is made in pioneering countries such as the Netherlands and the UK can be found in our forthcoming article in the IEEE Power & Energy Magazine.

[25] A bi-level model was developed to capture strategic behavior in flexibility markets. A detailed description of the model and findings can be found in EUniversal Deliverable 10.3 [36]: Regulatory recommendations for flexibility options and markets, and Strategic behaviour in flexibility markets: New games and sequencing options. Energy Syst. Integr. Model. Group. Work. Pap. Ser. No. ESIM2021-05 [37].

[26] The different approaches to contract flexibility are described in more detail in [35]. A qualitative analysis of the compatibility of different ways to contract flexibility is described in EUniversal Deliverable 5.1 [38], and EUniversal D10.3 [36].

Regulatory sandboxes can be a tool to create insights into the contracting of flexibility by DSOs in a real environment. Therefore, we examined the interaction between the design of the legal framework for regulatory sandboxes and its potential to bring innovation. We found that to promote innovation, the regulatory scope of the sandboxes should be as open as possible while keeping it tangible for project applicants. This can be achieved by including multiple regulatory entities in the administration process of the sandbox and highlighting interesting innovations to project applicants. Besides, we observed that a call-based application process for regulatory sandboxes favors prioritizing specific topics such as the contracting of flexibility but should be continuously evaluated to keep up with the latest innovations.[27] In EUniversal D10.3 on 'Regulatory Recommendations for flexibility options and markets' we compare sandbox design criteria across Europe and propose design recommendations on several dimensions: application process, eligible project promoters, derogations, administration, length of derogations, funding, transparency and reporting.

[27] The findings are based on the analysis of legal frameworks on regulatory sandboxes in Austria, Brussels, Flanders, France, Germany, Great Britain, the Netherlands, Norway, Spain and Wallonia. A detailed analysis can be found in EUniversal Deliverable 10.3 [36].

4. UMEI API SRA

4.1 Motivation and methodology

The Universal Market Enabling Interface (UMEI) developed within the EUniversal project materializes into publicly available Application Programming Interfaces (APIs) that support the interactions between the different actors and the new flexibility markets. These APIs have been specified in EUniversal deliverables D2.4 [27] and D2.5 [28].

For every technical development, an SRA helps to determine the potential of a solution to be replicated outside the demonstration sites, and how it can increase its range of action, or the number of actors involved. When analyzing Information and Communication Technologies (ICT), two approaches can be differentiated: quantitative (e.g., simulations or laboratory experiments of communications between the devices/systems involved in a use case) or qualitative (e.g., aspects such as interoperability, robustness, or reliability).

A quantitative approach to analyze the UMEI API is not appropriate for two reasons. First, because the communications would be done through the internet, which is difficult to simulate accurately, and because it does not rely on ad-hoc communication infrastructures as other solutions. And secondly, because an API following a Representational State Transfer (REST) architecture, which is the case of the UMEI API, already provides great scalability from the technical point of view.

Qualitatively, by design, the UMEI API is conceived to be agnostic, adaptable, and modular, and to provide interoperability between DSOs, market parties, and platforms. This means that all the stakeholders should be able to implement it, regardless of the data models and standards they use in their systems (e.g., CIM, IEC 61850, etc.).

Despite the fact that these characteristics guarantee a great level of technical scalability and replicability, the implementation of an API may be facilitated or hampered by its design rules. That is to say, if other developers find it difficult to understand and use the designed API or following versions, the possibilities of replicating and scaling-up the UMEI are reduced. Therefore, the scalability and replicability of the UMEI API will be ultimately related to its understandability and reusability, which are achieved when the best practices for REST API development are applied [29].

To evaluate the quality of the UMEI API in these terms, a list of up to 69 best practices has been collected from existing guidelines and similar studies [29]–[33]. These best practices are divided into seven categories:

- **Uniform Resource Identifier (URI) design**. (Table 4.1) A list of best practices and common rules that would improve the understandability and reusability of the URIs by future developers that use the API.

- **Request methods**. (Table 4.2) The implementation of HTTP methods such as PUT, GET, POST, DELETE or HEAD, should follow some basic rules so that the API can be correctly implemented by future developers that use the API.

- **Error handling**. (Table 4.4) The practices in this category define some rules on how HTTP messages must be used as a response to a HTTP request method [29].

- **Metadata design**. (Table 4.5) The practices in this category specify how HTTP headers should be used to complete requests with metadata [29].

- **Representation design**. (Table 4.3) This category checks the consistency of the API to represent media type formats, schemas, resources, and error responses.

- **Client concerns**. (Table 4.6). Rules relevant for API clients.

- **Versioning**. (Table 4.7) This category provides the best practices in how the versions of the APIs should be identified [34]. This category is directly related to replicability, as a bad versioning system may make implementations of the API much more complex for developers.

To check the compliance of the UMEI API with this list of best practices, partners from WP2 were asked to fill in the checklist with a "Yes", "No", "Not sure", or "Not applicable N/A". The results obtained are discussed in the following subsection.

4.2 Results

Figure 4.1 shows the compliance of the UMEI API with the best practices for REST API design based on the information provided by WP2 partners. The score for each category, represented by a percentage, has been calculated by dividing the number of "Yes" (i.e., practices followed) by the total number of practices that could be applicable to UMEI. That is, those practices where the answer was "N/A" were not considered in the calculation. It must be highlighted that the UMEI API allows certain degree of freedom when implementing it, so some specific practices may be followed in some implementations and not in others. For this reason, Figure 4.1 shows two cases. The blue line represents the baseline case or worst-case scenario, that is, an implementation of the UMEI where none of the implementation-dependent practices are followed. On the other hand, the orange dashed line represents the potential case, which considers that all the best practices that may be followed during implementation are indeed applied.

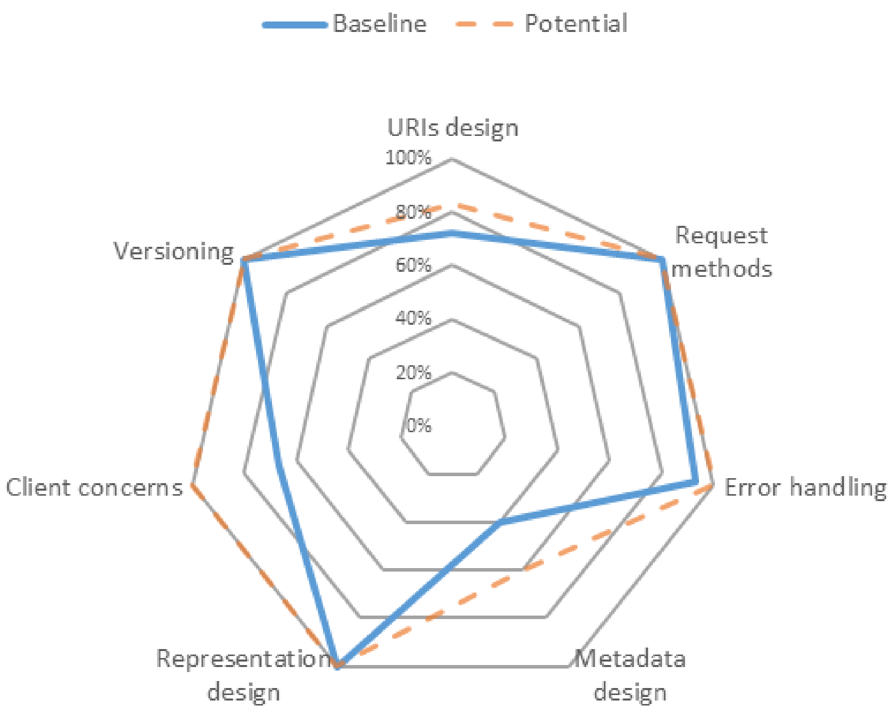


Figure 4.1: Compliance of the UMEI API with the best practices for the design of REST APIs that have an impact on its scalability and replicability.

Starting with how the **URIs are designed**, the UMEI API got a baseline score of 72.2% and a potential score of 83.3%. As shown by Table 4.1 three best practices were considered not applicable to the UMEI API so they were not considered to calculate these scores. There are two practices that are not followed:

- Using only lowercase letters in URI paths: the implementation of the UMEI API might be case sensitive. This may cause some trouble to developers in case an error arises during implementation due to this reason. Therefore, developers will have to pay special attention to the type of letters in URI paths.
- Avoiding version number in the path. It is expected that the UMEI API will include the version number in the URI path. Developers will have to know at every moment which API version they are using.

Table 4.1 Best practices for URIs design

Category: URIs design	Compliance
A trailing forward slash (/) should not be included in URIs	No
File extensions should not be included in URIs	Yes
A plural noun should be used for store names	Yes
A verb or verb phrase should be used for controller names	Yes
The query component of a URI may be used to filter collections or stores	Yes

Forward slash separator (/) must be used to indicate a hierarchical relationship	Yes
Hyphens (-) should be used to improve the readability of URIs	N/A
Underscores (_) should not be used in URI	Yes
Lowercase letters should be preferred in URI paths	No, implementation might be case sensitive
A singular noun should be used for document names	N/A
A plural noun should be used for collection names	Yes
Variable path segments may be substituted with identity-based values	N/A
Avoiding version number in the path	No
Avoiding version number in the query parameters	Yes
Avoiding CRUD actions in query parameters	Yes
Consistent subdomain names should be used for the API	NS (Implementation Specific)
CRUD function names should not be used in URIs	Yes
Use path variables to separate elements of a hierarchy, or a path through a directed graph	Yes
API as part of the subdomain	NS
The query component of a URI should be used to paginate collection or store results	Yes
Keeping as much information as possible in the URI, and as little as possible in request metadata	Yes

In addition to this, two best practices related to subdomains (using consistent subdomain names and including the API as part of the subdomain) depend on the specific implementation of UMEI.

For the best practices when using HTTP **request methods**, shown by Table 4.2, and **representation design**, shown by Table 4.3, the UMEI API got the maximum score of 100% in both the baseline and potential cases. Since the API is expected to not use the HEAD method, the rule associated to it was retrieved from the analysis.

Table 4.2 Best practices for request methods

Category: Request methods	Compliance
PUT must be used to both insert and update a stored resource	Yes
GET and POST must not be used to tunnel other request methods	Yes
GET must be used to retrieve a representation of a resource	Yes
POST must be used to create a new resource in a collection	Yes
POST must be used to execute controllers	Yes
DELETE must be used to remove a resource from its parent	Yes
HEAD should be used to retrieve response headers	N/A
PUT must be used to update mutable resources	Yes

Table 4.3 Best practices for representation design

Category: Representation design	Compliance
XML / JSON may optionally be used for resource representation	Yes
Minimize the number of advertised "entry point" API URIs	Yes
Consistent form to represent media type formats	Yes
Consistent form to represent media type schemas	Yes
Consistent form to represent error responses	Yes

The UMEI API also shows very good design in **error handling** with a score of 92.85% and 100% in the baseline and potential cases, respectively. As shown by Table 4.4, up to five practices were considered not applicable to the UMEI API, and only one depends on the implementation (HTTP error 304, "Not modified", that should be used to preserve bandwidth).

Table 4.4 Best practices for error handling

Category: Error handling	Compliance
200 ("OK") should be used to indicate nonspecific success	Yes
200 ("OK") should not be used to communicate errors in the response body	Yes
201 ("Created") must be used to indicate successful resource creation	Yes
202 ("Accepted") must be used to indicate successful start of an asynchronous action	N/A
204 ("No content") should be used when the response body is intentionally empty	Yes
301 ("Moved permanently") should be used to relocate resources	N/A
302 ("Found") should not be used	Yes
304 ("Not modified") should be used to preserve bandwidth	No (implementation specific)
400 ("Bad request") may be used to indicate nonspecific failure	Yes
401 ("Unauthorized") must be used when there is a problem with the client's credentials	Yes
403 ("Forbidden") should be used to forbid access regardless of authorization state	Yes
404 ("Not found") must be used when a client's URI cannot be mapped to a resource	Yes
405 ("Method not allowed") must be used when the HTTP method is not supported	Yes
406 ("Not acceptable") must be used when the requested media type cannot be served	N/A
409 ("Conflict") should be used to indicate a violation of resource state	N/A
412 ("Precondition failed") should be used to support conditional operations	N/A
415 ("Unsupported Media Type") must be used when the media type of a request's payload cannot be processed	Yes

500 ("Internal Server Error") should be used to indicate API malfunction	Yes
Use JSON as error message response	Yes

Regarding **metadata design**, it is the category where the UMEI API gets the lowest scores: 40% for the baseline, and 60% for the potential case. Table 4.5 shows that the UMEI API does not use content-length in the metadata and it also does not use location to specify the URI of a newly created resource. Depending on the implementation, caching may be used.

Table 4.5 Best practices for metadata design

Category: Metadata design	Compliance
Content-Length should be used	No
Location must be used to specify the URI of a newly created resource	No
Caching should be encouraged	No (implementation specific)
Content-Type must be used	Yes
Custom HTTP headers must not be used to change the **behavior** of HTTP methods	Yes

For the best practices regarding **client concerns**, the UMEI API gets a score of 66.67% for the baseline, and 100% for the potential case. However, it must be considered that the medium value of the baseline case is mainly caused by the reduced number of practices in this category (only three, as shown by Table 4.6). Depending on the implementation, Cross-Origin Resource Sharing (CORS) may be supported by the UMEI API to provide multi-origin read/write access from JavaScript.

Table 4.6 Best practices for tackle client concerns

Category: Client concerns	Compliance
The query component of a URI should be used to support partial response	Yes
CORS should be supported to provide multi-origin read/write access from JavaScript	NS (implementation specific)
New URIs should be used to introduce new concepts	Yes

For the last category, **versioning**, the UMEI API, as for the categories of request methods and representation design, also gets the maximum score of 100% for both the baseline and potential case. Table 4.7 shows that two practices were found to not be applicable to the UMEI API. However, in addition to the list of best practices for versioning, it was asked if the logic for handling the responses would change from one version to another, being the answer negative. In this case, [34] suggests, based on Apigee and Finnish Government's guidelines, to put the version on the HTTP header. This, which could be considered just a recommendation instead of a best practice, is something not covered by the current UMEI specification but that would depend on the specific implementation.

Table 4.7 Best practices for API versioning

Category: Versioning	Compliance
Increments major version when incompatible API changes are made	Yes
Increment minor version when functionalities are added in a backwards-compatible way	N/A
Increment patch version when backwards compatible bug fixes are made	N/A
Increment draft version when changes are made during the review phase that are not related to production releases	Yes
API extensions do not take anything away	Yes
API extensions de not change processing rules	Yes
API extensions do not make optional things required	Yes
Anything added in the API extension is optional	Yes

4.3 Interim conclusions

To get an overall idea of the quality of the UMEI, for this analysis it has been considered the outcome of the survey carried out by [29] about the importance of these practices perceived by eight expert developers. In that survey, the categories of URI design, HTTP request methods, error handling, and representation design are considered more relevant by developers. On the other hand, rules from the client concerns and metadata design categories were rated as less relevant. This means that, as long as an API performs reasonably well in the most relevant categories, a good level of understandability and reusability can be expected.

Results show that the UMEI API presents, in general, a good compliance of best practices of REST API design. UMEI follows all the rules for using HTTP request methods, versioning, and representation design. In certain implementations, the UMEI can also apply all the rules related to client concerns and error handling.

The category where the UMEI presents lower quality is metadata design, followed by the category of client concerns when considering the baseline case. Nevertheless, the best practices included in these two categories are the ones commonly considered by expert developers as the least relevant rules for API design [29]. In addition to this, the rules in these categories account for less than 12% of the list. Therefore, considering this, the scalability and replicability of UMEI are expected to not be strongly affected by the low scores in these categories.

As mentioned above, developers value more the best practices related to an appropriate URI design, a good use of HTTP request methods, good error handling, and a consistent representation design. These categories account for 77% of the best practices considered in this analysis. For these categories, as shown by Figure 4.1, the performance of the UMEI API is outstanding for the cases considered, so developers should not find many inconveniences when implementing UMEI according to its specification.

Regarding versioning, it was not considered by [29] in its survey. However, it can be considered a very relevant category to assure the scalability and replicability of an API; an API with a versioning system that follows the best practices will be easier to implement as it evolves. Results show that developers using the UMEI in future implementations should not have any problems to understand the functionality and usability of future versions of the API, given that all the best practices are followed and, during implementations, it can be even improved by putting the version on the HTTP headers. This sets a good basis for the replicability of the UMEI once the project finishes.

Despite the good performance of the UMEI regarding REST API design, it still has room for improvement concerning the seamless integration of additional actors and widening the scope in terms of market processes covered. Regarding the former, the UMEI may present some limitations as it relies on a given data model and format for the flexibility services that may not be universal. Regarding the latter, it is relevant to point out that the UMEI, as it stands now, focuses exclusively on the trading process, leaving out other relevant processes that could be integrated, such as the registration of flexibility resources.

In order to address these limitations and facilitate replicability, future developments of the UMEI could provide compatibility with other ontologies that are currently being developed in the smart grid ecosystem. For example, one potentially relevant ontology is the Smart Applications REFerence (SAREF) ontology, which is used for the description of the features and capabilities of smart devices by different stakeholders (service providers, developers, manufacturers, etc.). In addition to this, SAREF also provides compatibility with the oneM2M Base ontology, for Internet of Things (IoT) devices. Although the description of these devices could get adapted to the UMEI, its additional compatibility with SAREF would facilitate the registration and prequalification of smart devices and their overall integration in the market processes where UMEI is implemented.

In general, the scalability and replicability of UMEI will be good, based on its expected good understandability and reusability by developers, which are related to the application of most of the best practices enumerated in the specialized literature on the topic. This good understandability and reusability could be used to expand the UMEI, in a structured way, to provide compatibility with standardized ontologies. This would facilitate the integration of new actors in the market processes and further improve the scalability and replicability of the UMEI.

5. Conclusions

EUniversal comprises three different demonstrators located in Germany, Poland, and Portugal, in which ten Business Use Cases (BUCs) are being tested on real distribution networks. Most of these BUCs are focused on implementing local flexibility markets for the procurement of flexibility by DSO in the short- and long-term timelines. These markets aim to serve for the procurement and delivery of congestion management or voltage control services through active and/or reactive power.

The results from the demonstrators provide helpful practical information and hands-on experience on the project solutions. However, these results will be subject to the boundary conditions of each location and other real-life constraints. Therefore, complementing the demo results, the Scalability and Replicability Analysis (SRA) presented in this report helps understand the effects of implementing similar solutions under different technical conditions (e.g., network or FSP characteristics) and non-technical boundary conditions (e.g., regulatory conditions or business models). This section presents the main conclusions and takeaways obtained from this analysis.

The EUniversal SRA is divided into three main complementary elements:

iv. A simulation-based quantitative analysis modelling the operation of local flexibility markets for different services and products, and tested for different distribution grids and scenarios (functional SGAM layer).

v. A qualitative analysis focusing on how regulation, stakeholder views, or business model implementation can foster or hamper upscaling and replication of the BUCs (business SGAM layer).

vi. An analysis of the ease of understanding and reusing the UMEI API specification attending to its design features (information SGAM layer).

On the ensuing, the main results and conclusions obtained for these three dimensions are summarized.

Quantitative SRA: simulating local flexibility markets for different services and products in different distribution networks and scenarios

The quantitative SRA is based on the simulation of local flexibility market operation under different conditions. Nine different local market configurations combining three service specifications (congestion management, voltage control, or joint congestion management & voltage control) and three product availabilities (active power only, reactive power only, joint procurement of active and reactive power) were tested for four grids in the three demo countries. The Polish network analyzed is a rural MV grid expected to be subject to network constraints due to the foreseen increase in RES generation. For the German demo, two mostly residential MV+LV networks experiencing problems on the LV side due to growth in electric heating were considered. Lastly, a MV+LV distribution network expected to experience congestions and voltage issues both in the MV and LV levels driven by load electrification was analyzed.

In order to carry out the analyses, a linearized LFM modelling based on sensitivity factors was implemented. Once the distribution network models and the scenarios to be evaluated have been defined, the overall process can be summarized as follows. First, the flexibility needs and the relevant sensitivity factors depending on the market specifications (branch power flows and/or bus voltages, with respect to active and/or reactive power injection) have to be computed for the corresponding grid and scenario. Secondly, the FSP bids, in terms of volume, direction and price, are simulated depending on the specific capabilities defined for each type of FSP (load, generation or storage). Next, the local flexibility markets are cleared by deciding what FSP bids will be procured/activated so as to minimize costs to solve the previously calculated flexibility needs. After the market clearing, a post-evaluation is carried out by running a full AC power flow considering the flexibilities procured/activated so as to ensure that the clearing solution does not violate the operational limits set by the DSO. Lastly, the relevant KPIs are calculated including: number/share of avoided restrictions, cost of flexibility procurement, avoided CO2 emissions, increased RES and DER hosting capacity, and increase of energy storage solutions penetration.

Comparing the results obtained for each network under the different local market specifications and the results obtained for the different distribution grids, the following are the main general findings that have been identified:

- Markets where both active and reactive power flexibilities are jointly procured generally result in lower costs and are able to solve the same or more constraints. Moreover, active power only markets are generally more effective than reactive power only markets. In fact, results suggest that relying solely on reactive power may not be sufficient to effectively mitigate criticalities within the network. This conclusion stands regardless of the type of service procured.
- The previous conclusion can be explained by the fact that only MV and LV grids with relatively high R/X ratios are evaluated. Moreover, reactive power costs have been assumed to be significantly lower than active power costs, especially for inverter-based FSPs and synchronous generation (CHP, if available). Lastly, the co-optimization of active and reactive power allows for unlocking the voltage regulation potential offered by the capability curve of the resources, allowing for an operating point that optimizes flexibility provision.
- Multi-service markets, i.e., single market for congestion and voltage management, are generally more effective and efficient than single-service markets. However, they may be considered too complex for implementation. It is generally observed that each market model has a direct impact on the related criticality, i.e., CM markets reduce the congested lines and VC markets improve bus voltages, but it cannot be ensured that solving one type of constraint solves the other. In fact, in some cases, solving one type of constraint actually caused additional problems concerning the other type as shown in the post-evaluation. This happened, for instance, when significant (low-cost) reactive power flexibilities were activated to solve congestions causing voltage limit violations not seen within the market itself (no prior grid prequalification or "traffic-light" limitations were placed on the bids).
- Concerning the previous point, voltage control only markets were closer to the multi-service market models in terms of their effectiveness in avoiding restrictions as compared to pure congestion management markets. This implies that the same FSPs that solve bus voltage violations (with a stronger locational nature) can reduce the loading of upstream congested elements (even if located in different voltage levels), whereas flexibility bids cleared in the congestion management market models do not contribute to solving bus voltage issues. This happens when voltage issues share the same root cause as congestions, i.e. when flexibility solutions are not conflicting, and the two needs can be solved simultaneously. This happened in, for instance, the Portuguese grid, but not in the Polish one where congestions and undervoltages took place in different parts of the grid at different times of the day.

- On the other hand, in the Portuguese case where congestions happen in the MV grid and undervoltage issues on the LV, the standalone congestion management market is not able to solve any voltage problems because the least expensive flexibility source to solve MV congestions is connected to the MV grid, with no or negligible impact on the LV voltages. Therefore, in the scenarios studied for the Portuguese demonstrator, the voltage control actions are also beneficial for congestion management, acting as an implicit network congestion management measure.
- Voltage limits have a very strong impact on the number of grid criticalities and flexibility needs. Results show that increasing the maximum steady-state voltage variation limits from ±5% to ±7% results in a significant increase in the hosting capacity without any additional action. It remains to be seen whether flexibility may help DSOs relax some (conservative) operational limits.
- Likewise, results suggest that liquidity in local flexibility, which can be a major limitation to their effectiveness, is complex to quantify. This is because flexibility needs must be met in terms of quantity, location, direction (e.g., upward flexibility cannot be easily provided by RES generation) and time (e.g., some FSPs are not available to solve constraints caused by electric heating at night).

Qualitative SRA: open issues in regulation and business models that may drive or hamper upscaling and replication

Scalability and replicability can be heavily influenced by non-technical boundary conditions related to regulation, economic, or stakeholder-related factors. Therefore, the technical analysis is complemented with a qualitative assessment of these non-technical boundary conditions. More specifically, three main aspects have been addressed:

- First, the main open regulatory questions in congestion management in European distribution grids are revised.
- Second, the replicability of the flexibility business model as defined in EUniversal is evaluated.
- Lastly, a set of regulatory recommendations to enable the growth of flexibility markets in Europe is provided.

Concerning the first of these items, i.e., the main open questions regarding congestion management in European Distribution grids, the aspects analyzed included whether congestions in distribution grids are actually expected to increase or grind planning should prevent it, what mechanisms do DSOs resort to procure flexibility, what flexibility sources are more useful in what situations, does DSO revenue regulation need enhancement, or how can DSO-TSO coordination be ensured. Based on the assessment carried out, the following key takeaways were found:

1. DSOs in some European countries increasingly face congestion in their grids due to the connection of renewables, electric vehicles, and new loads. Heatmaps or hosting capacity maps are typically used by DSOs to report congestion issues to grid users.
2. Current distribution planning practices show the need for increased investments in the coming years to manage congestion levels and enable flexibility. However, there is no consensus yet on its actual potential to defer or avoid grid investments.
3. Third-party market platforms are tapping into this opportunity for flexibility, by quickly growing. These flexibility markets are used by DSOs for different reasons

and have developed diverse products, time-frames, and interactions with existing markets and system operators.

4. Issues such as the incentives for DSOs to use flexibility as an alternative to grid investments, the best approach for DSOs to contract flexibility and the coordination between the DSO and other stakeholders such as the TSO, are still unclear.
5. The procurement of flexibility for voltage control, as a separate product, will also become important for distribution grids.

The second element included in the qualitative SRA is the replicability of the EUniversal flexibility business models. More specifically, three main aspects of the business models are assessed, namely: i) what parts of the business model are purely local and must be custom built every time a flexibility market is implemented, ii) what elements of the business model can be replicated in future projects, and iii) the link between flexibility market tools for either congestion management or voltage control.

In summary, the results show that opening a flexibility market in a new location carries challenges due to the local nature of flexibility needs, network topology, regulation (if applicable), and resource availability. Nevertheless, here we conclude that the flexibility business model has important elements that can be conceptually applied across different locations. Specifically, the value proposition, communication channels and standards, and the logic behind costs and revenues can be exported to new implementations.

Lastly, a set of regulatory recommendations to enable the growth of flexibility markets in Europe was identified in the qualitative SRA.

- Recommendation 1: encourage the use of congestion and voltage heatmaps and the development of guidelines on the trade-off between flexibility and grid investments to advance the planning of distribution grids.
- Recommendation 2: given the existing uncertainties, it is recommended to keep an open mind regarding the way DSOs will contract flexibility and gain insights about the local interactions at play. Options include mandatory or voluntary participation, or short-term or long-term procurement.
- Recommendation 3: design open, tangible and up-to-date legal frameworks for regulatory sandboxes to foster innovation in the use of flexibility in distribution grids. This would imply keeping a wide regulatory scope of the possible exemptions granted under the sandboxes, and, if call-based applications are adopted, continuously evaluate the outcomes to keep up with the latest innovations.

Analysis of the replicability potential of the UMEI API specification

The EUniversal UMEI is a publicly available API that support the interactions between the different actors and the new flexibility markets. By design, the UMEI API is conceived to be agnostic, adaptable, and modular, and to provide interoperability between DSOs, market parties, and platforms. This means that all the stakeholders should be able to implement it, regardless of the data models and standards they use in their systems. Nonetheless, the implementation of an API may be facilitated or hampered by its design rules, i.e., if users find it difficult to understand and use the designed API or following versions, the possibilities of replicating and scaling-up the UMEI are reduced. Thus, to evaluate the ease of replicability of the UMEI API, a list of best practices has been identified. Compliance with these best practices was then evaluated through a questionnaire filled-in by the UMEI original developers.

Results show that the UMEI presents, in general, a good level of compliance of best practices of REST API design. UMEI follows all the rules for using HTTP request methods, versioning, and representation design. In certain implementations, the UMEI can also apply all the rules related to client concerns and error handling. The category where the UMEI rates lower quality is metadata design, followed by the category of client concerns when considering the baseline case. Nevertheless, the best practices included in these two categories are the ones commonly considered by expert developers as the least relevant rules for API design. Hence, thanks to its understandability and reusability, developers should not find many inconveniences when implementing UMEI according to its specification.

Despite the good performance of the UMEI regarding REST API design, there is still room for improvement concerning the seamless integration of additional actors and widening the scope in terms of market processes covered. Regarding the former, the UMEI may present some limitations as it relies on a given data model and format for the flexibility services that may not be universal. Regarding the latter, it is relevant to point out that the UMEI, as it stands now, focuses exclusively on the trading process, leaving out other relevant processes that could be integrated, such as the registration of flexibility resources.

In order to address these limitations and facilitate replicability, future developments of the UMEI could provide compatibility with other ontologies in the smart grid ecosystem (e.g., SAREF). This could facilitate the registration and prequalification of smart devices and their overall integration in the market processes where UMEI is implemented.

6. References

[1] O. Valarezo, R. Cossent, E. Beckstedde, and L. Meeus, "Deliverable D10.2 - Methodology and scenarios for the EUniversal Scalability and Replicability Analysis," 2022. [Online]. Available: https://euniversal.eu/wp-content/uploads/2022/01/EUniversal_D10.2_Methodology-and-scenarios-for-the-EUniversal-SRA.pdf. [Accessed: 11-Apr-2023].

[2] J. Vanschoenwinkel *et al.*, "EUniversal Deliverable D2.2: Business Use Cases to unlock flexibility service provision," 2021. [Online]. Available: https://euniversal.eu/wp-content/uploads/2021/05/EUniversal_D2.2.pdf. [Accessed: 10-Jan-2022].

[3] F. Bockemühl *et al.*, "EUniversal D8.1 - Specifications and guidelines of tools for an Active LV grid for field testing," 2022.

[4] M. Matusewicz *et al.*, "EUniversal D9.1: Demonstration of grid observability and future networks supporting flexibility management via the UMEi," 2022.

[5] M. Enabling *et al.*, "EUniversal D7.1: Portuguese Demonstrator - Demonstration of the UMEI concept in the management of market driven flexibility services for a LV and MV grid," no. 864334, 2020.

[6] L. Thurner *et al.*, "Pandapower - An Open-Source Python Tool for Convenient Modeling, Analysis, and Optimization of Electric Power Systems," *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 6510–6521, 2018, doi: 10.1109/TPWRS.2018.2829021.

[7] A. Papavasiliou, "Analysis of distribution locational marginal prices," *IEEE Trans. Smart Grid*, vol. 9, no. 5, pp. 4872–4882, 2018, doi: 10.1109/TSG.2017.2673860.

[8] J. F. Franco, L. F. Ochoa, S. Member, R. Romero, and S. Member, "AC OPF for Smart Distribution Networks : An Efficient and Robust Quadratic Approach," *IEEE Trans. Smart Grid*, vol. 9, no. 5, pp. 4613–4623, 2018, doi: 10.1109/TSG.2017.2665559.

[9] A. Sanjab, Y. Mou, A. Virag, and K. Kessels, "A Linear Model for Distributed Flexibility Markets and DLMPs: A Comparison with the SOCP Formulation," in *CIRED 2021 Conference*, 2021.

[10] C. Gouveia *et al.*, "EUniversal D4.1: Tools for the multi-level preventive control of flexibility resources in distribution networks and cooperation with TSO," 2022.

[11] F. Retorta, C. Gouveia, G. Sampaio, R. Bessa, and J. Villar, "Local flexibility need estimation based on distribution grid segmentation," *Int. Conf. Eur. Energy Mark. EEM*, vol. 2022-September, 2022, doi: 10.1109/EEM54602.2022.9920997.

[12] A. J. Conejo and L. Baringo, *Power System Operations*. Springer, 2018.

[13] E. Anderson *et al.*, "EUniversal Deliverable D6.2: Definition KPI for DEMOS," 2021. [Online]. Available: https://euniversal.eu/wp-content/uploads/2021/08/EUniversal_D6.2__Definition-KPI-for-DEMOs.pdf. [Accessed: 10-Jan-2022].

[14] I. Staffell and S. Pfenninger, "Using bias-corrected reanalysis to simulate current and future wind power output," *Energy*, vol. 114, pp. 1224–1239, 2016, doi: 10.1016/j.energy.2016.08.068.

[15] "Piclo Energy Website." [Online]. Available: https://www.piclo.energy/. [Accessed: 11-Apr-2023].

[16] M. Braun, "Provision of ancillary services by distributed generators : Technological and economic perspective," University of Kassel, 2008.

[17] M. Troncia, J. P. Chaves-Ávila, F. Pilo, and T. Gomez, "Remuneration mechanisms for investment in reactive power flexibility," *Sustain. Energy, Grids Networks*, vol. 27, p. 100507, 2021, doi: 10.1016/j.segan.2021.100507.

[18] D. Davi-Arderius, M. Troncia, and J. J. Peiró, "Operational Challenges and Economics in Future Voltage Control Services," *Curr. Sustain. Energy Reports*, vol. 4, no. 0123456789, 2023, doi: 10.1007/s40518-023-00218-1.

[19] ACER/ CEPA, "Study on the estimation of the Value of Lost Load of electricity supply in Europe," no. July, pp. 1–116, 2018.

[20] European Commission, "PVGIS: PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM." [Online]. Available: https://re.jrc.ec.europa.eu/pvg_tools/es/. [Accessed: 12-Jun-2023].

[21] T. Buber, S. Von Roon, A. Gruber, and J. Conrad, "Demand Response potential of electrical heat pumps and electric storage heaters," *IECON Proc. (Industrial Electron. Conf.*, pp. 8028–8032, 2013, doi: 10.1109/IECON.2013.6700475.

[22] ERSE, "Perfis de consumo, de produção fotovoltaica e de autoconsumo a aplicar entre 1 de janeiro de 2023 e 31 de dezembro de 2023." [Online]. Available: https://www.erse.pt/inicio/. [Accessed: 25-Jul-2023].

[23] E. Beckstedde and L. Meeus, "From 'Fit and forget' to 'Flex or regret' in distribution grids," *IEEE Power Energy Mag.*, vol. 21, no. June, pp. 45–52, 2023, doi: 10.1109/MPE.2023.3269545.

[24] European Commission., "DIRECTIVE (EU) 2019/944 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on common rules for the internal market for electricity and amending Directive 2012/27/EU (recast)," *Off. J. Eur. Union*, p. L 158/125-199, 2019.

[25] EUROELECTRIC, Eurostat, IEA, EDSO, and M. Deloitte, "Connecting the dots: Distribution grid investment to power the energy transition." [Online]. Available: https://www.eurelectric.org/connecting-the-dots/. [Accessed: 10-Jul-2023].

[26] E. Beckstedde *et al.*, "EUniversal Deliverable D10.1: Business model canvas and comparison of CBA methodologies," 2021. [Online]. Available: https://euniversal.eu/wp-content/uploads/2021/08/EUniversal_D10.1_Business-model-canvas-and-comparison-of-CBA-methodologies.pdf. [Accessed: 10-Jan-2022].

[27] L. Fonseca *et al.*, "EUniversal D2.4: UMEI API functional specification of DSO Interface for standardized market platforms Interaction," 2021.

[28] C. Silva *et al.*, "EUniversal D2.5: UMEI prototype," 2021.

[29] F. Petrillo, P. Merle, N. Moha, and Y. G. Guéhéneuc, "Are REST APIs for cloud computing well-designed? An exploratory study," *Springer Int. Publ.*, vol. 9936 LNCS, pp. 157–170, 2016, doi: 10.1007/978-3-319-46295-0_10.

[30] S. Kotstein and J. Bogner, "Which RESTful API Design Rules Are Important and How Do They Improve Software Quality? A Delphi Study with Industry Experts," in *Communications in Computer and Information Science*, 2021.

[31] M. Masse, *REST API Design Rulebook*. O'Reilly Media, Inc., 2011.

[32] M. Stowe, *Undisturbed REST: A guide to designing the perfect API*. MuleSoft, 2015.

[33] C. Rodriguez, M. Baez, D. Florian, F. Casati, and J. Trabucco, "REST APIs: A Large-Scale Analysis of Compliance with Principles and Best Practices," in *Lecture Notes in Computer Science*, 2016, doi: 10.1007/978-3-319-38791-8 2.

[34] L. Murphy, T. Alliyu, A. Macvean, M. B. Kery, and B. A. Myers, "Preliminary Analysis of REST API Style Guidelines," in *PLATEAU'17 Workshop on Evaluation and Usability of Programming Languages and Tools*, 2017, pp. 1–9.

[35] L. Meeus, E. Beckstedde, and A. Nouicer, "Towards a regulatory framework for the use of flexibility in distribution grids," *Oxford Energy Forum*, vol. The Future, no. 134, 2022.

[36] E. Beckstedde *et al.*, "EUniversal D10.3: Regulatory recommendations for flexibility options and markets," no. 864334, pp. 1–41, 2022.

[37] E. Beckstedde, L. Meeus, and E. Delarue, "Strategic behaviour in flexibility markets: new games and sequencing options," *Energy Syst. Integr. Model. Gr.*, no. Working Paper Series No. ESIM2021-05, 2021.

[38] EUniversal, "Deliverable: D5.1 Services, Identification of relevant market mechanisms for the procurement of flexibility needs and grid," no. 864334, 2020.

Annex I – Overview of EUniversal BUCs

Table 0.1: EUniversal BUCs general information

Demo	BUC ID	BUC Name	Demo Locations	Grid Level	Prioritization from D2.2
Germany	DE-AP	Congestion management & Voltage Control with market-based active power flexibility	**East of Germany:** South Brandenburg, South Saxony-Anhalt, and West and South Saxony Region.	**Focused on LV grid.** However, the transition from LV to MV (provision of aggregated LV flexibility for the MV level) is being examined.	**Mandatory**
	DE-RP	Congestion management & Voltage Control with market-based reactive power flexibility			**Mandatory**
Poland	PL-AP	Congestion management & Voltage Control with market-based active power flexibility	**Different locations (north and central parts of Poland):** HV grid (ENERGA-OPERATOR's HV network – **DLR functionality**), MV grid (North near the city of Wladyslawowo), LV grid (region of Plock, Kalisz, Gdansk).	HV, MV, and LV grids	**Mandatory**
	PL-RP	Congestion management & Voltage Control with market-based reactive power flexibility		HV, MV, and LV grids	**Mandatory**
	PL-DLR	Congestion management using permissible line capacity based on Dynamic Line Rating (DLR) system		HV, MV, and LV grids	**Optional**
	PL-FS	Voltage control with the use of flexstation solutions		HV, MV, and LV grids	**Optional**
Portugal	PT1	Congestion management in MV grids for the day-ahead market (or between 1 to 3 days in advance)	**Different locations:** Valverde, West zone of Portugal, Alcochote, E-REDES EV charging infrastructures in urban areas.	LV and MV grids	**Mandatory**
	PT2	Integrated Voltage Control in MV and LV grids for the day-ahead market (AP+RP)		LV and MV grids	**Mandatory**
	PT3	Contracting flexibility services for avoiding voltage and/or congestion issues during planned maintenance action in MV grids		LV and MV grids	**Business need**
	PT4	Voltage control and congestion management for medium and long-term grid planning through market mechanisms		LV and MV grids	**Business need**

Annex II – Local flexibility market optimization model

OBJECTIVE FUNCTION:

The objective function of the LFM clearing is defined by three terms i) the minimization of the flexibility procurement cost including active and reactive power flexibility bids from FSPs ii) the minimization of not supplied flexibility for the voltage control component ($\alpha_{i,t}$), and iii) the minimization of not supplied flexibility for the congestion management component ($\beta_{l,t}$).

$$\min_{\Delta p, \Delta q, \alpha, \beta} \sum_{t=1}^{NT} \left\{ \sum_{f=1}^{NF} \left[\left(C_{f,t}^{U\_P} \Delta p_{f,t}^{U} + C_{f,t}^{D\_P} \Delta p_{f,t}^{D} \right) + \left(C_{f,t}^{U\_Q} \Delta q_{f,t}^{U} + C_{f,t}^{D\_Q} \Delta q_{f,t}^{D} \right) \right] + \sum_{i=1}^{N\_PB} C^{\alpha} \left| \alpha_{i,t} \right| + \sum_{l=1}^{N\_CL} C^{\beta} \left| \beta_{l,t} \right| \right\}$$

SUBJECT TO:

1. Flexibility matching constraint for congestion management:

$$\Delta S_{l,t}^{CL} <= \sum_{f=1}^{NF} \left[K_{l,f}^{P} \left(\Delta p_{f,t}^{U} - \Delta p_{f,t}^{D} \right) + K_{l,f}^{Q} \left(\Delta q_{f,t}^{U} - \Delta q_{f,t}^{D} \right) \right] + \beta_{l,t}; \ \forall_{l} \in N\_CL, \ \forall_{t} \in NT$$

2. Flexibility matching constraints for voltage control:

$$v_{i,t}^{B} - V_{i,t}^{A} = \sum_{f=1}^{NF} \left[H_{i,f}^{P} \left(\Delta p_{f,t}^{U} - \Delta p_{f,t}^{D} \right) + H_{i,f}^{Q} \left(\Delta q_{f,t}^{U} - \Delta q_{f,t}^{D} \right) \right] + \alpha_{i,t}; \ \ \forall_{i} \in N\_PB, \ \forall_{t} \in NT$$

$$V^{max} \leq v_{i,t}^{B} \leq V^{min} \quad \forall_{i} \in N\_PB, \ \forall_{t} \in NT$$

3. FSPs' flexibility bid limits:

$$0 \leq \Delta p_{f,t}^{U} \leq P_{f,t}^{Umax} \ ; \ \forall_{f} \in \mathrm{N}F, \forall_{t} \in \mathrm{NT}$$

$$0 \leq \Delta p_{f,t}^{D} \leq P_{f,t}^{Dmax} \ ; \ \forall_{f} \in \mathrm{N}F, \forall_{t} \in \mathrm{NT}$$

$$0 \leq \Delta q_{f,t}^{U} \leq Q_{f,t}^{Umax} \ ; \ \forall_{f} \in \mathrm{N}F, \forall_{t} \in \mathrm{NT}$$

$$0 \leq \Delta q_{f,t}^{D} \leq Q_{f,t}^{Dmax} \; ; \; \forall_f \in \mathrm{N}F, \forall_t \in \mathrm{NT}$$

4. FSPs' constraints: The following block of constraints represents the equations required for the modelling of three types of FSPs, load, generators, and storage. Each FSP type model consider capability limits when offer upward and downward flexibility for both active and reactive power.

$$\left(\Delta p_{f,t}^{U}, \Delta p_{f,t}^{D}, \Delta q_{f,t}^{U}, \Delta q_{f,t}^{D}, p_{f,t}, q_{f,t}, s_{f,t}\right) \epsilon \; \psi \; ; \; \forall_f \in \mathrm{N}F, \forall_t \in$$