

## RESEARCH ARTICLE

# Distribution System Operator Services: A Comparative Assessment of Multi-Product Co-Optimization for Congestion Management and Voltage Control Using a Local Flexibility Market

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**ABSTRACT** The increasing penetration of distributed energy resources into distribution grids poses significant planning and operational challenges for power systems, particularly for local congestion and voltage regulation. This paper presents an assessment of a multi-product and multi-service Local Flexibility Market (LFM) aimed at supporting distribution system operators (DSOs) in procuring flexibility products based on active (P) and reactive (Q) power for DSO services of congestion management (CM) and voltage control (VC). The proposed linearised LFM model incorporates AC sensitivity factors for network representation into the market-clearing formulation to capture non-linear interactions between flexibility procured from service providers and resulting grid impacts. Using a synthetic medium-voltage network derived from a real Polish grid, this paper evaluates the technical and economic performance of different service-product market designs (e.g. CMVC\_PQ) to address local network needs. The results demonstrate that jointly P and Q in an LFM for CM and VC can significantly reduce DSO network needs and total flexibility procurement costs, compared to traditional single-service or single-product approaches. These findings underscore the value of coordinated market designs in effective and cost-efficient flexibility deployment in distribution grids.

**INDEX TERMS** Active power, congestion management, DSO services, flexibility products, local flexibility markets, reactive power, voltage control.

## NOMENCLATURE

### ABBREVIATIONS

|      |  |
|------|--|
| AC   | Alternating current.                       |
| CM   | Congestion management.                     |
| CMVC | Congestion management and voltage control. |
| DC   | Direct current.                            |
| DER  | Distributed energy resource.               |

|      |                                |
|------|--------------------------------|
| DERs | Distributed energy resources.  |
| DSO  | Distribution system operator.  |
| DSOs | Distribution system operators. |
| KPIs | Key performance indicators.    |
| LFM  | Local flexibility market.      |
| LFMs | Local flexibility markets.     |
| LV   | Low voltage grid level.        |
| MV   | Medium voltage grid level.     |
| OLTC | On-load tap changer.           |
| P    | Active power.                  |

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|       |                                      |
|-------|--------------------------------------|
| PQ    | Active and reactive power.           |
| PTDFs | Power transfer distribution factors. |
| Q     | Reactive power.                      |
| R     | Resistance.                          |
| SP    | Service provider.                    |
| SPs   | Service providers.                   |
| SO    | System operator.                     |
| SOs   | System operators.                    |
| RESs  | Renewable energy sources.            |
| TSO   | Transmission system operator.        |
| TSOs  | Transmission system operators.       |
| TR    | Transformer.                         |
| VC    | Voltage control.                     |
| VSCs  | Voltage sensitivity coefficients.    |
| X     | Reactance.                           |

## I. INTRODUCTION

### A. BACKGROUND AND MOTIVATION

The ongoing transformation of power systems is being driven by the decentralised deployment of renewable energy resources (RESs), such as photovoltaic and wind, along with the widespread electrification of end uses, such as those related to heating and cooling, and transportation [1], [2]. These trends increase the variability and uncertainty of both electricity generation and demand, adding significant complexity to power system planning and operation. Consequently, System Operators (SOs) face new challenges in maintaining an efficient system functioning as power imbalances and bidirectional power flows become more frequent [3]. Furthermore, there is a growing incidence of network needs, such as overloads (exceeding thermal limits of lines and transformers) and voltage violations (under- and over-voltage at buses), particularly in distribution grids with high penetration of distributed energy resources (DERs) [1], [4]. Such DERs are often associated with localised power injections or withdrawals that can exceed the thresholds of existing infrastructure, which was not originally designed to handle them [5], [6].

Traditionally, network needs have been addressed through grid reinforcement measures, such as updating or expanding infrastructure in the affected areas [7], [8]. However, this approach is becoming less attractive due to the high investment costs and long implementation times [9]. An alternative is to leverage the intrinsic flexibility of power systems, which enables delaying or indefinitely deferring grid reinforcement until it becomes the most efficient solution. In this context, flexibility can be understood as the ability of power systems to exploit available resources to cope with the variability and uncertainty of electricity generation and consumption across relevant market timeframes, by adjusting supply or demand patterns in reaction to external signals, such as price incentives or activation requests [10], [11].

SOs can access flexibility through two main approaches: by using their own resources (e.g., network reconfiguration, capacitor banks, or power electronics) or by acquiring

services from third-party resources [11], [12]. The latter typically involves DERs, such as distributed generators, demand-side response, or storage systems, which can adapt their network usage according to grid requirements. Moreover, in recognition of this potential, European regulatory frameworks are increasingly promoting the use of flexibility [10], [13], and SOs are now expected to actively facilitate the integration of flexibility services to address local network needs.

Consequently, appropriate flexibility acquisition mechanisms are essential, which can be classified into four categories [14]: network tariffs, connection agreements, market-based procurement, and rule-based approaches. Depending on how signals are structured, flexibility provision can be implicit, such as in dynamic tariffs, or explicit, such as in local flexibility markets (LFMs) or flexible connection agreements. In implicit mechanisms, signals are embedded within the mechanism design to incentivise efficient customer behaviours, but the actual response from DERs remains voluntary and unpredictable. In contrast, explicit mechanisms establish a formal and direct procurement process in which participating DERs commit to deliver predefined services in exchange for compensation [2], [6]. These commitments are typically enforced through contractual obligations, including penalties for non-compliance, which enhances the reliability of the response from participants. In Europe, the Network Code for Demand Response [15], submitted to the European Commission in 2025 following stakeholder consultation and currently under review, designates market-based solutions as the preferred method for procuring local network services. Therefore, LFMs enable SOs to procure targeted flexibility services from DERs [8], which can participate as service providers (SPs), in a market-based environment, providing a feasible alternative to conventional solutions [16].

Flexibility services are essential for both transmission system operators (TSOs) and distribution system operators (DSOs). Although TSO–DSO coordination is relevant for flexibility deployment, it lies beyond the scope of this work. This study focuses on the distribution level, where congestion management (CM) and voltage control (VC) are particularly relevant and can be specifically designated as DSO services for this purpose. LFMs can provide a promising market-based mechanism for acquiring these DSO services.

In practice, particularly in transmission systems, CM and VC are often addressed separately, with CM typically relying on active power (P), while VC is commonly associated with reactive power (Q) [5]. However, in distribution systems, due to high R/X ratios and the coupled nature of AC power flows, the effects of active and reactive power on line loadings and voltage magnitudes cannot be disregarded. Therefore, active and reactive flexibility can contribute to both congestion management and voltage regulation. Despite these technical capabilities, reactive power flexibility remains underutilised, partly due to the limited technical infrastructure required for its practical deployment, as well as the lack of transparent and non-discriminatory mechanisms [17] that adequately reflect

its locational value and voltage sensitivity [5], [18]. This is particularly relevant because reactive power has traditionally been provided through mandatory services by large power plants, capacitor banks, and transformers with tap changers. However, the increasing incidence of voltage problems in distribution networks may require greater participation from third-party resources through emerging market-based mechanisms [19]. Although reactive power markets are still immature, their development should consider the interaction between P and Q, the cost components associated with Q provision, and the highly local nature of reactive power services.

In this context, integrated approaches that enable the joint procurement of CM and VC may facilitate the identification of synergies between services and products traditionally handled independently. This perspective is further supported by recent European initiatives and demonstrator projects, such as [20], [21], and [22], as well as broader implementation-oriented studies and real applications on flexibility market design and deployment [23], which illustrate how LFM-based approaches can effectively combine different DSO services and flexibility products, enabling scalable and replicable solutions across DSOs to minimise reinforcement needs and operational costs.

Additionally, an LFM-clearing can be formulated, employing or not the network data. There are many approaches to incorporate network data into market models, such as second-order cone programming, quadratically constrained programming, or linearisation of power flow equations [20], [24], but they can be computationally demanding, especially in large networks. Likewise, nodal AC optimal power flow-based market-clearing typically requires extensive grid information and significant computational effort, which may limit its practical applicability in distribution-level flexibility markets. This is particularly relevant in practical European LFM frameworks, where electricity and system service trading are organised through sequential market processes rather than an integrated nodal market-clearing scheme [23], [25].

Furthermore, only DSOs typically have access to detailed grid data [1], posing challenges for independent LFM operators and third-party flexibility stakeholders due to confidentiality and data-sharing limitations. As a practical alternative, sensitivity factors, such as Power Transfer Distribution Factors (PTDFs) or Voltage Sensitivity Coefficients (VSCs), can be employed to represent the network without requiring full data [24] and can be provided by DSOs [16]. However, these sensitivity factors are traditionally derived under a DC power flow approximation, which, despite its simplicity, neglects reactive power flows and assumes constant voltage magnitudes, thereby not accurately reflecting real grid behaviour. Accordingly, this work also adopts an LFM-clearing formulation based on AC sensitivity factors for network representation, which captures voltage magnitude variations, and the interactions between active and

TABLE 1. Comparison of strategies in key related studies.

| Ref. (year)             | Network Data  | DSO service |    |      | Flexibility product |   |    | Sensitivity factors |
|-------------------------|---|-------------|----|------|---------------------|---|----|---------------------|
|                         |   | CM          | VC | CMVC | P                   | Q | PQ |                     |
| [1] (2025)              | Real 359-bus radial MV/LV distribution grid (Finland) | ✓           | ✗  | ✗    | ✓                   | ✗ | ✗  | DC VSCs             |
| [28] (2025)             | Modified IEEE 69-bus radial MV distribution grid      | ✓           | ✗  | ✗    | ✓                   | ✗ | ✗  | -                   |
| [7] (2023)              | IEEE 33-bus radial MV grid                            | ✓           | ✗  | ✗    | ✓                   | ✗ | ✗  | -                   |
| [29] (2021)             | Synthetic 15-bus radial MV grid                       | ✓           | ✗  | ✗    | ✓                   | ✗ | ✗  | DC PTDFs            |
| [16] (2025)             | Real 41-bus radial MV/LV distribution grid (Bosnia)   | ✓           | ✓  | ✗    | ✓                   | ✗ | ✗  | DC PTDFs, VSCs      |
| [30] (2022)             | Synthetic 5-bus radial grid                           | ✓           | ✗  | ✗    | ✓                   | ✗ | ✗  | AC PTDFs (only P)   |
| [3] (2022)              | Synthetic (33–2079 bus) radial MV distribution grids  | ✓           | ✓  | ✗    | ✓                   | ✓ | ✓  | -                   |
| <b>This work</b> (2026) | Synthetic 22-bus radial MV grid (Poland)              | ✓           | ✓  | ✓    | ✓                   | ✓ | ✓  | AC PTDFs, VSCs      |

reactive power flows, key aspects for effective congestion management and voltage control.

**B. RELATED WORKS**

Many published studies focus on developing technical control-based strategies to address overload and voltage problems, such as those presented in [4], [26], and [27]. By contrast, only a few previous works adopt a market-based perspective by considering the provision of DSO services using P or Q through LFMs, as summarised in Table 1. It compares main characteristics of these studies in terms of the network data, the targeted DSO services (CM: only congestion management, VC: only voltage control, CMVC: Both simultaneously), the flexibility products considered (P: only active power, Q: only reactive power, PQ: Both simultaneously), and the type of sensitivity factors employed for network representation, when applicable (e.g. PTDF).

Reference [1] addresses CM in distribution grids by procuring active power flexibility via LFMs, and employs a matrix-based representation of VSCs. It shows that larger zones improve liquidity but may worsen voltages in distribution grids, underlining trade-offs when CM relies

solely on P. Paper [28] proposes an LFM framework for CM that enables cross-grid flexibility procurement from adjacent distribution networks. It relies on active-power flexibility, while voltage improvements are treated as a co-benefit rather than as an explicitly procured VC or reactive power service. Besides, [7] presents a two-stage distributed market model combining a local energy market and an incentive-based LFM that procures P for CM, demonstrating improved social welfare by relieving grid overload without restricting prior energy trading. This study recommends incorporating reactive power and complementary markets to support voltage regulation. In addition, work [29] introduces a continuous LFM model that incorporates the network representation through DC PTDFs. The paper acknowledges its limitations in capturing the characteristics of distribution grids and suggests extending the framework to LFMs for active and reactive power, along with a more accurate grid representation based on AC power flows.

In turn, [16] develops a dynamic co-simulation platform to analyse how the location of flexibility assets affects their impact on distribution grid services. It introduces an iterative LFM-clearing approach integrating DC PTDFs and VSCs to reflect grid conditions. The results show that location-aware clearing methods significantly improve the efficiency of congestion mitigation and voltage regulation, especially when both technical and economic criteria are considered. Furthermore, [30] proposes a continuous trading LFM for distribution systems based on AC network sensitivities, considering only active power. Since the framework is mainly oriented to congestion management, it also highlights the need for future enhancements toward coordinated voltage support, multi-constraint management, and a deeper assessment associated with AC-sensitivity-based clearing formulations. Finally, work [3] presents a day-ahead LFM that reduces overloads and voltage problems, solved with a successive linear programming optimal power flow, tailored for distribution networks. Active power is traded among participants, while reactive power is supplied to the DSO through remunerated contracts. This joint approach minimises overloads and voltage violations, demonstrating high accuracy and scalability across different network conditions.

The aforementioned works differ in the DSO services, the flexible products, and the grid representation in the LFM model. Only a few studies explicitly consider Q or joint procurement PQ. As a result, a significant gap remains in assessing the integrated flexibility procurement of P and Q for CM and VC. Also, some works use DC sensitivity factors with limited accuracy, while others rely on detailed grid data at a higher computational cost. Therefore, this work fills those gaps by proposing a multi-product, multi-service LFM model that incorporates AC sensitivity factors.

### C. SCOPE AND MAIN CONTRIBUTIONS

In response to the identified gaps, this paper presents a quantitative assessment of different service-product market

designs for LFMs. The analysis supports the comparison in terms of flexibility procurement and their effectiveness in mitigating overloads and voltage violations, under an AC sensitivity-based LFM-clearing formulation. Specifically, this paper makes the following contributions:

- **Assessment of single-service versus multi-service market designs:** We develop an LFM model to assess the techno-economic performance of procuring CM, VC, or both CMVC. The model co-optimises service-product market designs to minimise flexibility procurement costs while considering operational constraints.
- **Comparative analysis of flexibility products:** The LFM model enables the trading for flexibility products of P-only, Q-only, or both PQ, to evaluate their effectiveness in providing DSO services.
- **Use of AC sensitivity factors for network representation:** The LFM model incorporates AC PTDFs and VSCs into the market-clearing formulation to reflect voltage variations and reactive power flows, linking procured flexibility from SPs to actual grid response.

Note that this paper focuses on quantifying the impact of service-product market designs under the adopted experimental setup. In this sense, the insights derived from the analysis can support strategic decision-making for network management and future infrastructure investments, even though the operational infrastructure required for practical implementation is not yet fully available. The study is conducted using a realistic MV distribution network, where suitable DER technologies can provide active and/or reactive flexibility for DSO services. While reactive power controllability remains limited across several DER technologies and distribution levels, particularly in low-voltage networks, it can play a significant role in supporting voltage regulation and congestion management at medium- and high-voltage levels [31]. Accordingly, the objective of this assessment is to compare different combinations of flexibility products and DSO services within a common market-clearing framework. The development of a complete LFM process (e.g., pre-qualification, bidding rules, activation/dispatch instruction, monitoring and settlement) lies beyond the scope of the present work.

### D. PAPER ORGANISATION

This paper is organised as follows: Section II describes the methodology developed to guide this study. Section III details the experimental setup, including the definition of service-product market designs, network model, and characterisation of SPs. Section IV presents the formulation of the LFM model. Section V presents simulation results comparing the performance of different flexibility products (P, Q, PQ) for DSO services (CM, VC, CMVC). Finally, Section VI concludes the paper, summarising the main findings and their implications for LFM-based flexibility procurement.

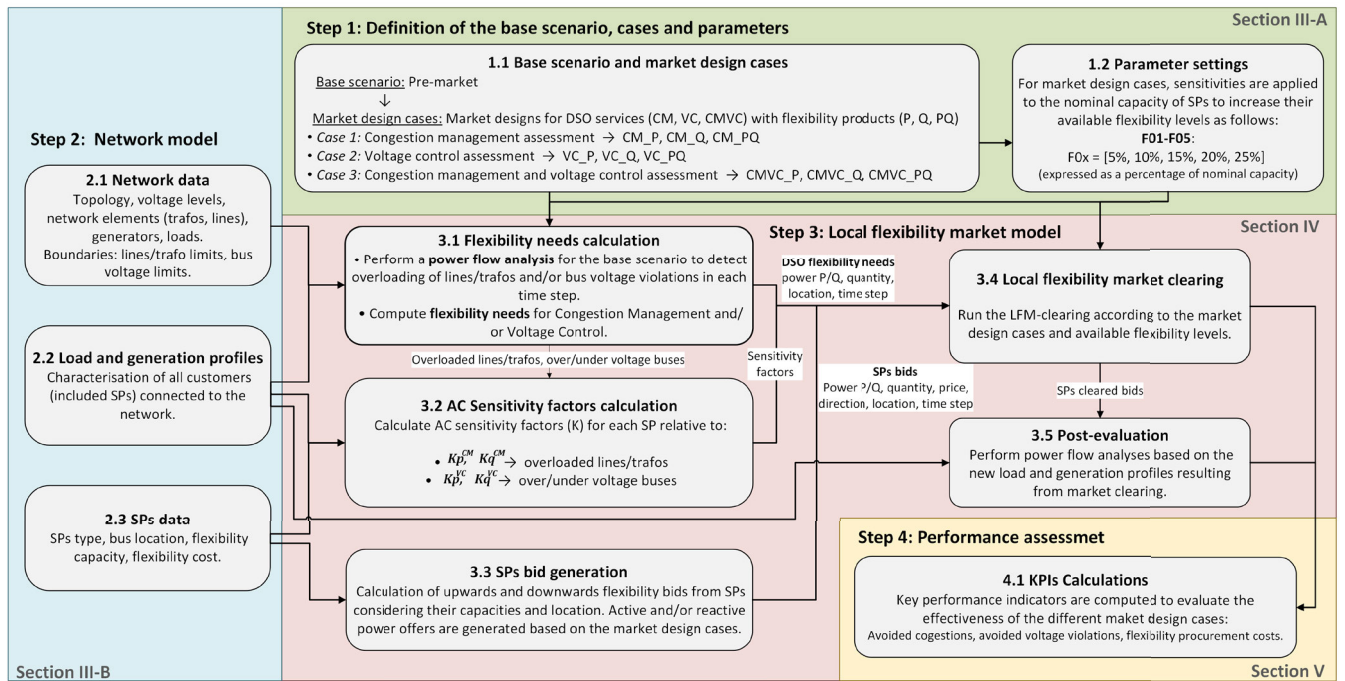


FIGURE 1. Methodology adopted to guide this study. Each step includes the paper section where it is described.

II. METHODOLOGY

Figure 1 presents the four-step methodology developed to guide this study and maps the corresponding section for each step. A brief overview is provided below:

**Step 1: Definition of the base scenario, cases, and parameters:** The base scenario (without flexibility procurement) serves as the benchmark for analysis. Building on this base scenario, the market design cases and parameter settings are established to assess their potential to address local network needs. Details are provided in Section III-A.

**Step 2: Network model:** This step compiles the input data to represent the distribution grid, including network topology, load and generation profiles, and characterisation of SPs. The grid is modelled using the open-source power system analysis tool PandaPower [32]. Further details in Section III-B.

**Step 3: Local Flexibility Market model:** The LFM is modelled as an optimisation problem that incorporates in the market-clearing formulation the AC sensitivity factors to represent the network model, and the flexibility procurement costs. The LFM model is detailed in Section IV. The optimisation was performed using Gurobi Optimizer (v10.0), executed on a Windows server with a 2.10 GHz processor and 128 GB of RAM. This step is subdivided into five sub-steps:

3.1. *Flexibility needs calculation:* A power flow analysis is conducted for the base scenario to detect overloads in lines and transformers, as well as buses with under-voltage or over-voltage conditions. The network needs are computed as DSO flexibility needs for CM and VC accordingly.

3.2. *AC sensitivity factors calculation:* AC Sensitivity coefficients are employed to represent the network in the LFM model. Note that these AC sensitivity factors influence the optimal selection of SP bids in the market-clearing, which also accounts for bid prices and available flexibility. In this way, accepted bids are determined by both economic and technical criteria, as the optimisation accounts for both bid prices and the impact of each SP on the targeted network constraints through AC sensitivity factors. Therefore, bid selection is not based solely on the offered price in the SP bid.

3.3. *SPs bid generation:* Upward and downward flexibility bids for active and reactive power are generated based on SP flexibility capacities, technology, and costs for each time step according to the market design cases.

3.4. *Local flexibility market clearing:* The market is cleared to select the most cost-efficient flexibility bids to meet the DSO flexibility needs for CM and/or VC. This step considers DSO flexibility needs computed in Step 3.1, AC sensitivity factors from Step 3.2, bids from Step 3.3, and parameters from Step 1. The LFM is settled under a pay-as-bid scheme, i.e., accepted offers are paid at their bid prices [33]. Bids are assumed to be submitted at their marginal provision cost, and pricing mainly affects payments rather than market feasibility.

3.5. *Post-Evaluation:* An ex-post power flow analysis is performed to verify that the cleared bids comply with the operational limits defined by the DSOs, given the simplified network representation based on sensitivity factors. This validation step identifies remaining or newly introduced

overloads and voltage violations that may arise from insufficient flexibility availability, unsuitable SP locations, or approximation errors associated with the sensitivity-based market-clearing formulation. In addition, tolerance margins are incorporated into the operational constraints to mitigate the risk of infeasible post-clearing operating conditions. If unacceptable operating conditions still persist after the validation step, additional corrective actions or iterative market-clearing procedures may be required, although these aspects are beyond the scope of the present work.

**Step 4: Performance assessment:** Technical and economic Key Performance Indicators (KPIs) are calculated to assess the performance of different service-product market designs. It includes: avoided congestion (reduction in congestion problems), avoided voltage violations (reduction in voltage problems), and flexibility procurement total costs.

LFMs can be organised according to two main operational paradigms: DSO-driven flexibility procurement (corrective or curative paradigm), or ex-ante allocation of network access rights (preventive paradigm) [34], [35], [36]. In the first, network users operate freely, and the DSO manages congestion by procuring flexibility services. In the second, users must secure network capacity or operating limits in advance. A detailed discussion of the regulatory principles and implications associated with these two organisational paradigms is beyond the scope of this paper. However, the product type comparison is agnostic with respect to this paradigm, as embedded in the network impact, the procurement paradigm only affects the market sequence, roles and responsibilities of actors, and cashflow structure. A comprehensive techno-economic comparison of these paradigms, together with an assessment of their regulatory implications, is left for future research given that the modelling framework developed in this work is sufficiently flexible to represent both paradigms.

### III. DESCRIPTION OF THE EXPERIMENTAL SETUP

#### A. DEFINITION OF THE BASE SCENARIO, CASES AND PARAMETERS

The base scenario (pre-market) represents the initial condition without LFM clearing or flexibility procurement from SPs. It serves as a baseline to evaluate the effectiveness of different service-product market designs in addressing overloads and voltage violations. Building on this base scenario, the following market design cases are considered:

**Case 1 (Congestion management assessment):** Grid overloads typically arise from thermal capacity limitations in transformers or feeders. In case 1, the procurement of flexibility by SPs has been assessed considering three different flexibility products: only active power (CM\_P), only reactive power (CM\_Q), and both (CM\_PQ), to evaluate their contributions in reducing the number of overloads.

**Case 2 (Voltage control assessment):** Voltage violations in distribution networks are often the consequence of over-voltages due to high penetration of DERs, particularly when reverse power flows occur, or under-voltages resulting

from heavy loading conditions, especially at the end of long feeders. Case 2 evaluates the role of the procurement of flexibility by SPs for maintaining bus voltages within allowed limits. Three flexibility products are considered: only active power (VC\_P), only reactive power (VC\_Q), and both (VC\_PQ).

**Case 3 (Congestion management and voltage control assessment):** Addressing overloads and voltage violations independently may lead to suboptimal use of the available flexibility and higher operational costs. Case 3 explores the co-optimised procurement of flexibility for CM and VC. Three flexibility products are assessed: only active power (CMVC\_P), only reactive power (CMVC\_Q), and both (CMVC\_PQ). The latter provides the most comprehensive multi-service and multi-product strategy for addressing multiple network needs through a single market-clearing step.

Additionally, sensitivity parameters are applied to the nominal capacities of SPs to progressively increase their upward and downward flexibility bids. Five levels are considered, from 5% to 25% in 5% increments (F01 to F05). This enables the assessment of how higher flexibility availability from SPs affects network problem mitigation and the associated costs.

#### B. NETWORK MODEL: GRID TOPOLOGY AND DER SPECIFICATIONS

The electrical grid illustrated in Figure 2 represents the synthetic MV distribution network employed in this study, intended to replicate the characteristics of a real-world application (Polish demonstrator from the EUniversal project [20], [37]). This grid comprises a 22-bus radial topology fed by two 110/30-15 kV three-winding transformers (TR-1 and TR-2), each rated at 40/20-20 MVA. The network includes three main MV feeders at 15 kV and two feeders at 30 kV to interconnect DERs. The lines R/X ratio is approximately 1.5965.

The system integrates 7 distributed generators: 4 wind farms (WF 3, 4, 5, 10 at 15 kV), 1 biogas power plant (BGP 12 at 15 kV), and 2 gas-fired combined heat and power plants (CHP20, 21 at 30 kV). The demand is modelled through 8 aggregated loads (Loads 3, 6, 8, 9, 11, 13, 16, 17), representing combined household, commercial, and industrial consumption. The load and generation profiles have been adjusted based on real data for each resource type, using representative days of network usage conditions.

Since the original network does not exhibit overloads or voltage violations, the pre-market scenario was derived by scaling these profiles under peak-day oversupply conditions to intentionally trigger network problems. This approach is applicable to current networks experiencing operational constraints or for anticipating future scenarios with increased loading conditions. Furthermore, without loss of generality, deterministic profiles are employed, and uncertainty in renewable generations and demand is not considered, as this is not expected to change the relative insights across

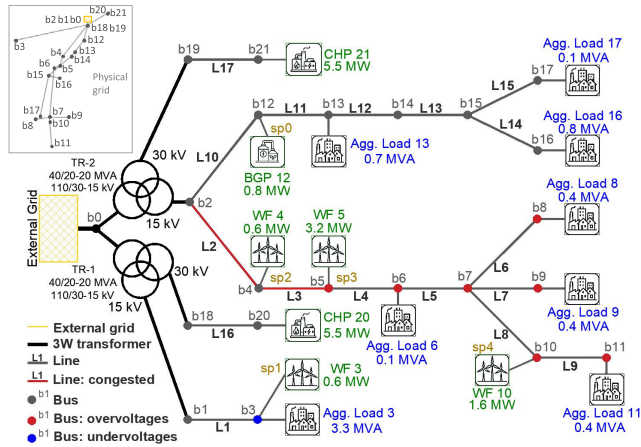


FIGURE 2. Synthetic MV distribution network adapted from the polish demonstrator [37].

market designs, although it may affect absolute outcomes (e.g., procured volumes and costs). For further details, refer to [20].

Furthermore, five of the aforementioned DERs (located on buses b3, b4, b5, b10, b11) are considered as SPs, each offering active and reactive power flexibility based on their type and nominal capacity, as shown in Table 2.

TABLE 2. SPs data from the polish demonstrator [37].

| SP id | Description        | SP type    | Nominal capacity [MVA] | Active power upward/downward capacity [%] | Reactive power upward/downward capacity [%] |
|-------|--------------------|------------|------------------------|---|---|
| sp0   | Biogas power plant | Generation | 0.8                    | 5% / 5%                                   | 5% / 5%                                     |
| sp1   | Wind farm          |            | 0.6                    |   |   |
| sp2   | Wind farm          |            | 0.6                    |   |   |
| sp3   | Wind farm          |            | 3.2                    |   |   |
| sp4   | Wind farm          |            | 1.6                    |   |   |

The flexibility procurement costs for P and Q are based on data from LFMs for CM in the UK [20], derived from statistical analysis considering clearing prices for similar products. The SPs are assumed to bid at their marginal cost for flexibility provision. Reference costs for P are randomly assigned to the different SPs, following a normal distribution with a mean of 39.78 [€/MWh] and a standard deviation of 0.244 [€/MWh]. The bid unitary costs for Q [€/MVarh] were set at 5% of the P cost, assuming that the reactive power costs are due to internal active power losses of the electronic equipment required to keep the reactive power set-point, according to the study presented in [31].

#### IV. LOCAL FLEXIBILITY MARKET MODEL

This section presents the LFM model developed in this study to procure P and Q from SPs for CM and VC.

#### A. AC SENSITIVITY FACTORS FOR CONGESTION MANAGEMENT AND VOLTAGE CONTROL

In this approach, AC sensitivity factors are computed for each SP participating in the LFM, based on the specific DSO flexibility need for congestion management and voltage control, as shown in Figure 1 in step 3.2.

AC PTFDs, computed via a small finite perturbation in the apparent power magnitude exchanged by the considered SP, are employed as sensitivity factors for CM. They describe how the apparent power  $S$  flowing through the congested element  $ce$  (overloaded lines and transformers) can be modified by injections or withdrawals in the active ( $Kp_{ce,i,t}^{CM} = dS_{ce,t}/dP_{i,t}$ ) or reactive ( $Kq_{ce,i,t}^{CM} = dS_{ce,t}/dQ_{i,t}$ ) power provided by the considered SP  $i$ , in each time step  $t$ .

AC VSCs, computed via a small finite perturbation in the voltage magnitude exchanged by the considered SP, are employed as the sensitivity factors for VC. They represent how the voltage  $V$  at a specific bus  $pb$  (under- or over- voltage buses) can be modified by injections or withdrawals in active ( $Kp_{pb,i,t}^{VC} = dV_{pb,t}/dP_{i,t}$ ) or reactive ( $Kq_{pb,i,t}^{VC} = dV_{pb,t}/dQ_{i,t}$ ) power provided by the considered SP  $i$ , in each time step  $t$ .

For each time step  $t$ , AC PTFDs and VSCs are computed around the corresponding pre-market operating point, obtained from an AC power flow (including voltage magnitudes/angles and network losses). In addition, discrete controls (e.g, OLTC/tap positions) are kept fixed at the base operating point values for that time step.

#### B. OBJECTIVE FUNCTION

The objective function of the LFM model considers three main components, as expressed in (1), as shown at the bottom of the next page.

- **Flexibility procurement costs:** Minimisation of the total flexibility procurement cost, both active ( $\Delta P$ ) and reactive ( $\Delta Q$ ), from SPs across the different resource categories over all time steps. The resource categories include flexibility upward (increased generation or decreased consumption) and flexibility downward (decreased generation or increased consumption).
- **Non-supplied flexibility costs for congestion management:** Minimisation of unmet flexibility needs in congested elements (overloaded lines and transformers).
- **Non-supplied flexibility costs for voltage control:** Minimisation of unmet voltage regulation needs at pilot buses (under- or over-voltage buses).

where  $\Delta P_{k,i,t}$  and  $\Delta Q_{k,i,t}$  correspond to the active and reactive power flexibility cleared volumes, respectively, for the resource  $i$  in category  $k$  at time  $t$ . The upward and downward bid prices for active and reactive power flexibility are indicated as  $c_i^{P(k)}$  and  $c_i^{Q(k)}$ , respectively. The amount of non-supplied flexibility for congestion management, in congested elements  $ce$ , is represented by  $\beta_{ce,t}$ , while  $\alpha_{pb,t}$  corresponds to the amount of non-supplied flexibility for voltage control in the pilot bus  $pb$ .  $VOLL$  is the value of the lost load, acting as a penalty for unmet flexibility needs.

In this case study, a value of 6260 [€/MWh] is used, as it corresponds to the estimated value for Poland [37]. The parameter  $\left| \overline{K}p_{t,pb}^{VC} \right|$  corresponds to the active power sensitivity coefficient of bus  $pb$  at time  $t$ , used to normalise the unit measurement of this term within the objective function.  $T$  is the full-time horizon.

**C. FLEXIBILITY CLEARING CONSTRAINTS FOR CONGESTION MANAGEMENT AND VOLTAGE CONTROL**

In CM and VC, the effectiveness of flexibility is inherently dependent on the electrical point of injection and on the network topology and impedance, i.e., identical  $\Delta P$  and  $\Delta Q$  bids at different SP buses lead to different impacts on line/transformer loadings and bus voltages [20]. For this reason, the LFM clearing model incorporates a network representation based on AC sensitivity factors. This allows the LFM to avoid procuring flexibility that may appear inexpensive but is electrically ineffective for alleviating the targeted network constraints. Such inefficient procurement can occur in price-only (matchmaker) LFMs, or when DC sensitivity factors are used, as these do not capture voltage effects and reactive power interactions within the network.

The congestion management constraint in (2) for the LFM-clearing formulation aims to alleviate overloading in lines and transformers by ensuring that the aggregated flexibility procurement of both products,  $\Delta P_{k,i,t}$  and  $\Delta Q_{k,i,t}$ , considering the network model through the active ( $Kp_{k,t,ce,i}^{CM}$ ) and reactive ( $Kq_{k,t,ce,i}^{CM}$ ) sensitivity factors, meet the required shift in power flow ( $\Delta S_{ce,t}$ ) in congested elements.

$$\Delta S_{ce,t} - \sum_{\substack{\text{Resource } i \in N_{SP(k)} \\ \text{Category}}} \sum (Kp_{k,t,ce,i}^{CM} \cdot \Delta P_{k,i,t} + Kq_{k,t,ce,i}^{CM} \cdot \Delta Q_{k,i,t}) - \beta_{ce,t} \leq 0, \quad \forall ce \in N_{CongestedElements}, \forall t \in T \tag{2}$$

where  $\beta_{ce,t}$  corresponds to unserved flexibility for congestion management penalised in the objective function.

In parallel, voltage control constraints are defined at the specific under- or over-voltage buses (pilot buses) to ensure the voltage magnitude remains within allowable

limits ( $V^{Min}$  and  $V^{Max}$ ). The LFM market-clearing model incorporates the procured flexibility, both active  $\Delta P_{k,i,t}$  and reactive  $\Delta Q_{k,i,t}$  products, in response to voltage magnitude variations by using voltage sensitivity coefficients ( $Kp_{k,t,pb,i}^{VC}$  and  $Kq_{k,t,pb,i}^{VC}$ ), as defined in equations (3) to (7). The voltage shifts at each pilot bus  $pb$  are calculated based on whether the pre-LFM voltage  $V_{pb,t}^{Before}$  exceeds or falls below the operational limits.

If  $V_{pb,t}^{Before} > V^{Max}$ :

$$V_{pb,t}^{After} - V_{pb,t}^{Before} - \alpha_{pb,t} - \sum_{\substack{\text{Resource } i \in N_{SP(k)} \\ \text{Category}}} \sum (Kp_{k,t,pb,i}^{VC} \cdot \Delta P_{k,i,t} + Kq_{k,t,pb,i}^{VC} \cdot \Delta Q_{k,i,t}) \geq 0 \tag{3}$$

If  $V_{pb,t}^{Before} < V^{Min}$ ,  $\forall pb \in N_{PilotBus}, \forall t \in T$ :

$$V_{pb,t}^{After} - V_{pb,t}^{Before} - \alpha_{pb,t} - \sum_{\substack{\text{Resource } i \in N_{SP(k)} \\ \text{Category}}} \sum (Kp_{k,t,pb,i}^{VC} \cdot \Delta P_{k,i,t} + Kq_{k,t,pb,i}^{VC} \cdot \Delta Q_{k,i,t}) \leq 0 \tag{4}$$

Otherwise:

$$V_{pb,t}^{After} - V_{pb,t}^{Before} - \alpha_{pb,t} - \sum_{\substack{\text{Resource } i \in N_{SP(k)} \\ \text{Category}}} \sum (Kp_{k,t,pb,i}^{VC} \cdot \Delta P_{k,i,t} + Kq_{k,t,pb,i}^{VC} \cdot \Delta Q_{k,i,t}) = 0 \tag{5}$$

where  $\alpha_{pb,t}$  corresponds to unserved flexibility for voltage control, penalised in the objective function.

Note that, in distribution grids, P and Q injections/withdrawals affect thermal loading and voltage magnitudes to a similar extent. PTFDs and VSCs are employed to represent thermal loading and voltage sensitivities, while the LFM formulation considers the impact of both active and reactive flexibility on the market-clearing constraints.

Furthermore, the post-LFM voltage,  $V_{pb,t}^{After}$ , must remain within the predefined minimum and maximum limits,

$$\min_{\substack{\Delta P_{k,i,t}, \\ \Delta Q_{k,i,t}, \\ \beta_{ce,t}, \\ \alpha_{pb,t}}} \left\{ \sum_{t \in T} \left[ \left( \sum_{\substack{\text{Resource } i \in N_{SP(k)} \\ \text{Category}}} c_i^{p(k)} \cdot \Delta P_{k,i,t} + c_i^{q(k)} \cdot \Delta Q_{k,i,t} \right) + \left( \sum_{ce \in N_{CongestedElements}} VOLL \cdot |\beta_{ce,t}| \right) + \left( \sum_{pb \in N_{PilotBus}} VOLL \cdot \left( \frac{|\alpha_{pb,t}|}{\left| \overline{K}p_{t,pb}^{VC} \right|} \right) \right) \right] \right\} \tag{1}$$

adjusted by a tolerance margin  $\Delta V_{\text{tol}}$ , as expressed in (8).

$$\begin{aligned} V^{\text{Min}} + \Delta V_{\text{tol}} &\leq V_{pb,t}^{\text{After}} \leq V^{\text{Max}} - \Delta V_{\text{tol}} \\ \forall pb \in N_{\text{PilotBus}}, \quad \forall t \in T \end{aligned} \quad (8)$$

#### D. FLEXIBILITY BID LIMITS OF SERVICE PROVIDERS

This set of constraints in (9) defines the admissible range of upward and downward, active and reactive power flexibility that each SP can offer at each time step. These limits reflect the technical capabilities of the flexible assets and ensure that the bids remain within their operational boundaries.

$$\begin{aligned} 0 &\leq \Delta P_{k,i,t} \leq P_{k,i,t}^{k,\text{max}} \\ 0 &\leq \Delta Q_{k,i,t} \leq Q_{k,i,t}^{k,\text{max}} \\ \forall k \in \text{Resource Category}, \quad \forall i \in N_{\text{SP}(k)}, \quad \forall t \in T \end{aligned} \quad (9)$$

#### E. SERVICE PROVIDER CONSTRAINTS.

The group of constraints in (10) represent the operational constraints  $\Phi$  required to model the SPs, as classified in Table 2. Each SP type considers technical capability limits when offering upward and downward flexibility for both P and Q. These constraints ensure that flexibility bids are technically feasible and aligned with the operational characteristics of the respective technology (i.e., load, generator, storage).

$$\begin{aligned} (\Delta P_{k,i,t}, \Delta Q_{k,i,t}, P_{k,i,t}, Q_{k,i,t}, S_{k,i,t}) &\in \Phi; \\ \forall k \in \text{Resource Category}, \quad \forall i \in N_{\text{SP}(k)}, \quad \forall t \in T \end{aligned} \quad (10)$$

Note that the specific SP formulations are not detailed, as they generally follow the resource models commonly adopted in the literature. Moreover, such formulations can be tailored to the application, as this work focuses on the LFM design rather than detailed modelling of individual resources.

Furthermore, the LFM is modelled as an event-based tender that is triggered only when the DSO forecasts a potential violation of network constraints during a specific period. This modelling choice reflects the operational nature of many European DSO-oriented LFMs [23], which are typically activated only when and where network problems are anticipated. Accordingly, the LFM is formulated as a sequence of independent single-period clearing problems, with one market time unit per time step. Inter-temporal constraints of SPs, such as storage state-of-charge limits, energy budgets, demand response duration or rebound effects, are therefore not explicitly represented in the market-clearing formulation. Instead, such constraints are assumed to be managed internally by SPs when defining their flexibility bids and availability, reflecting a decentralised operational approach commonly adopted in local flexibility procurement frameworks [25].

This assumption is adopted to maintain a linear and computationally tractable formulation suitable for the comparative assessment of different service-product market designs.

While inter-temporal constraints could be incorporated in the formulation, doing so would significantly increase the computational burden without altering the comparative insights derived from the analysis. In this framework, the feasibility of SP actions is instead ensured through the definition of per-period capability limits, bid assumptions, and predefined initial operating conditions.

## V. RESULTS AND DISCUSSIONS

This section follows the steps in Figure 1, and covers: (A) pre-market conditions in the base scenario to compute DSO flexibility needs, (B) post-market technical assessment of market design cases to handle network problems, (C) post-market economic assessment to obtain flexibility procurement costs, and (D) multi-service and multi-product assessment.

### A. BASE SCENARIO: PRE-MARKET

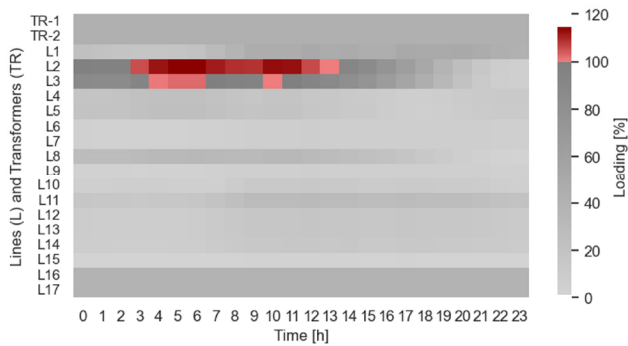
In the base scenario, a 24-hour power flow analysis is performed to detect network needs, serving as the basis for estimating the required DSO flexibility needs. Figure 3 shows the loading percentage [%] of all lines and transformers, while Figure 4 illustrates the voltage magnitudes [p.u.] at all buses. Greyscale shading denotes that the values fall within acceptable limits. In total, 15 congestions and 84 voltage violations (78 over-voltages and 6 under-voltages) are identified.

Figure 3 shows that two lines experience overloads,  $L2$  and  $L3$ , during several hours, as indicated by the red colour scale. No congestion is observed in transformers. Similarly, Figure 4 illustrates voltage violations in some buses. The under-voltages are represented by shades of blue, corresponding to voltage levels below the minimum threshold ( $V^{\text{Min}} = 0.95$  [p.u.]), while the over-voltages, depicted in shades of red, indicate values exceeding the maximum threshold ( $V^{\text{Max}} = 1.05$  [p.u.]). Bus  $b3$  exhibits under-voltage problems, while buses  $b5$  through  $b11$  are affected by over-voltage problems. In both figures, more intense colours correspond to more severe deviations from the allowable operational limits.

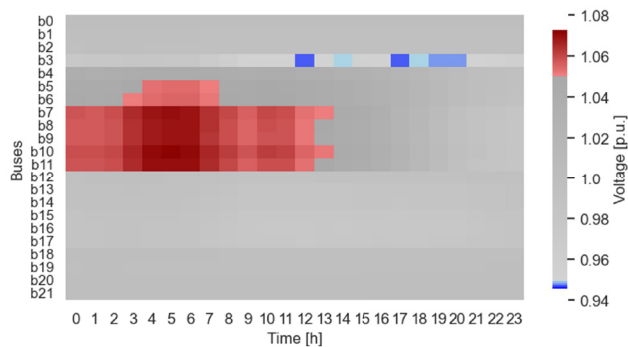
These network problems are also illustrated in Figure 2, where  $sp2$ ,  $sp3$  and  $sp4$  are connected in the feeder of the congested lines and over-voltage buses, and  $sp0$  on another feeder but linked to the same transformer  $TR-2$ , highlighting their direct potential to provide flexibility. In parallel,  $sp1$  may mitigate the under-voltages at bus  $b3$ , which is connected to another transformer,  $TR-1$ . This allows assessing how both SP groups address network problems under common market rules, while accounting for their physical separation.

### B. POST-MARKET TECHNICAL RESULTS

Figure 5 compares the overloads of lines and transformers across the market design cases and the available flexibility levels (F01-F05), relative to the base scenario. Figure 5(a) displays bar charts showing the number of overloads identified in the base scenario (framed in red) and service-product



**FIGURE 3.** Loading percentages [%] of lines and transformers in the base scenario. Blocks in red represent congested elements.



**FIGURE 4.** Bus voltages [p.u.] in the base scenario. Blocks in red represent over-voltage. Blocks in blue represent under-voltage.

market designs (others). Figure 5(b) depicts the distribution of loading percentages of all lines and transformers over the full simulation time horizon, in the base scenario (red) and in response to flexibility procurement for the service-product market designs (coloured curves, one colour per flexibility product). Specifically, each curve shows how frequently loading percentage values fall within different loading percentage ranges, considering all lines/transformers and time steps. This offers a broader view of network utilisation, revealing how the overall loading profile shifts across service-product market designs. The red dotted vertical line indicates the 100% loading threshold, which defines thermal congestion.

Similarly, Figure 6 compares voltage violations at buses. Figure 6(a) illustrates the number of voltage violations, broken down into under-voltages (blue bars) and over-voltages (red bars). Figure 6(b) presents the distribution of bus voltage magnitude at all buses in the base scenario (red) and in response to flexibility procurement (coloured curves, one per flexibility product). Specifically, each curve shows the frequency with which voltage magnitudes fall within different per-unit voltage ranges, considering all buses and time steps. This provides a broader system-level view of voltage conditions in the network, showing the overall voltage profile shifts across service-product market designs. The vertical red dashed lines at 0.95 [p.u.] and 1.05 [p.u.] mark voltage bounds beyond which voltage violations occur.

In Case 1, to assess the impact on overloads, Figure 5(a) shows that flexibility procurement through P-only (purple) or

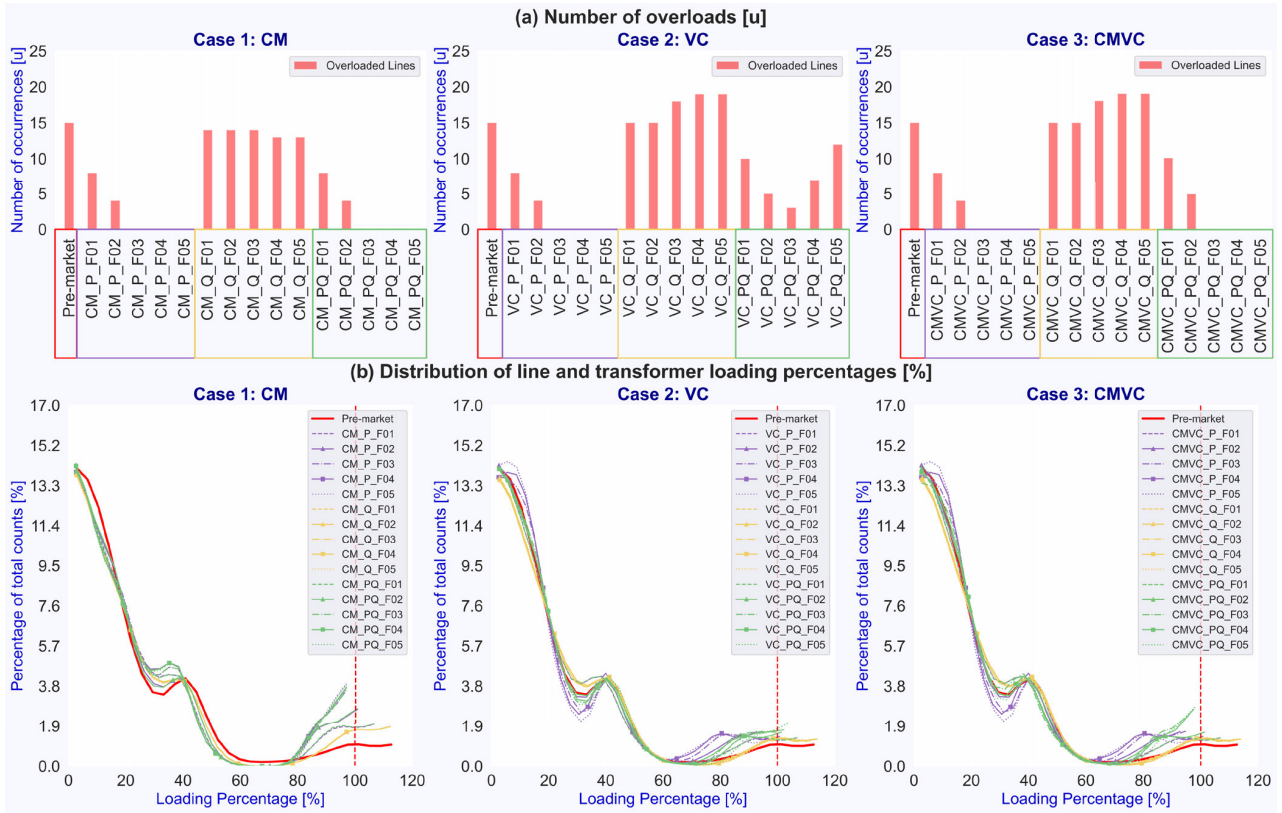
PQ (green) can fully resolve congestion at higher available flexibility levels (F03–F05), evidencing the correlation of congestion mitigation on available active power flexibility. This is supported by the distribution curves in Figure 5(b), where procurement of P results in a leftward shift in loading percentages, especially around the threshold, indicating an overall reduction in line and transformer loading. In contrast, Q-only (yellow) has a negligible impact on reducing congestion numbers, achieving at most a 13.3% (F04, F05).

Regarding voltage violations in Case 1, Figure 6(a) shows that over-voltages are only slightly mitigated with P-only or worsen in Q-only and PQ. This is also reflected in the distribution plots of Figure 6(b), where bus voltages tend to shift beyond the upper bound. In addition, the number of under-voltage problems is reduced by 83.3% relative to the base scenario, and the distribution plots tend to shift rightward, toward the lower voltage bound. The unresolved voltage violations, regardless of the level of flexibility available, are likely explained by the fact that CM markets are primarily designed to address overloads rather than voltage problems.

In Case 2, Figure 5(a) shows that P procurement can reduce overloads as in Case 1, which is reflected in the leftward shift of the loading distribution curves (purple) in Figure 5(b). On the other hand, Q-only has a negligible or even an adverse effect on network loading, given the nature of both VC markets and Q, which primarily impact voltages rather than power flows. This is important in distribution grids due to high R/X ratios, where Q can increase losses and, if uncoordinated, worsen overloads. Regarding voltage violations, Figure 6 shows that both P-only and Q-only reduce over-voltages as flexibility levels increase (F03–F05), being better than Case 1, which is consistent with the voltage regulation constraints in the market-clearing formulation. The Q-only performs slightly worse than the P-only in these market designs. Similarly, for under-voltages, Case 2 is less favourable compared to Case 1. In both, the results show that VC markets require larger volumes of Q to address voltage problems.

For PQ market designs, although over-voltage violations are solved at higher flexibility levels, overloads may worsen, particularly beyond F03. This suggests a potential trade-off or conflict between DSO service objectives when Q is procured, as the market-clearing may prioritise voltage regulation, potentially at the expense of thermal loading limits. Consequently, the LFM allocates flexible resources in ways to address the most critical or cost-effective constraints, meaning that not all network problems are resolved equally, especially those that are not directly targeted in the market-clearing step.

In Case 3, P-only and Q-only have similar impacts on overloads and voltage violations as in Case 2, leading to comparable technical outcomes. The joint procurement of active and reactive power flexibility yields the most favourable results, particularly at higher flexibility levels, where almost all network problems are resolved, highlighting the added



**FIGURE 5.** Network congestion indicators comparing the base scenario with the different service-product market designs. (a) Bar plots illustrating the number of overloads. (b) Loading percentage distribution of all lines and transformers [%].

value of co-optimised flexibility procurement. Thus, based on the results shown in Figure 5 and Figure 6, from a technical perspective, CMVC\_PQ market design offers a well-balanced trade-off between congestion relief and voltage regulation.

**C. POST-MARKET ECONOMIC RESULTS**

The economic performance of each service-product market design is evaluated by analysing the total flexibility costs arising from the LFM-clearing step and its potential to address network needs. It includes the direct costs associated with the cleared flexibility volumes of P and Q, as well as penalties for unmet DSO flexibility needs. Thus, Figure 7 summarises the costs of the procured active (blue bars) and reactive (orange bars) power, aggregated upward and downward, and the costs of non-provided flexibility  $\beta_{ce,t}$  for CM (green bars), and non-provided flexibility  $\alpha_{pb,t}$  for VC (red bars). Note that when the  $\beta_{ce,t}$  cost component is zero in CM markets, it indicates that all congestions are mitigated. Likewise, a zero  $\alpha_{pb,t}$  cost in VC markets implies that all voltage violations are solved.

In Case 1, higher total flexibility costs are mainly driven by penalties for unmet flexibility needs due to unresolved overloads. The Q-only market design (CM\_Q) yields the highest total costs in this case, because it fails to effectively address network needs. On the other hand, under CM markets with P-only and PQ in higher available flexibility levels

(F03-F05), where congestions are successfully mitigated, these costs are reduced considerably. The combined procurement of P and Q (CM\_PQ) yields about 1.6% lower total costs than P-only (CM\_P). This case, despite the seemingly lower flexibility costs, fails to address over-voltage problems (Figure 6).

In Case 2, the total flexibility costs are higher than in Case 1, mainly driven by penalties for unresolved voltage violations. Voltage control services with P-only (VC\_P) require higher volumes of active power than in Case 1, but resolve overloads and over-voltage problems in F05. The Q-only (VC\_Q) costs are under 3% of P-only costs, but the market design remains insufficient to solve network needs. The VC\_PQ shows an important reduction in total costs compared to P-only, and mitigates over-voltage problems at higher flexibility levels (F04-F05), but may increase overloads (Figure 5).

Case 3 shows the highest total flexibility costs, as it includes penalties for unresolved congestions and voltage violations. As before, Q-only design (CMVC\_Q) results in the greatest total costs due to unmet flexibility needs. The procurement of P-only (CMVC\_P) incurs higher costs than PQ, primarily driven by remaining voltage violations that are not resolved through active power procurement alone. In contrast, the combined procurement (CMVC\_PQ) proves to be the most cost-effective and technically viable option, especially at higher flexibility levels (F04-F05),

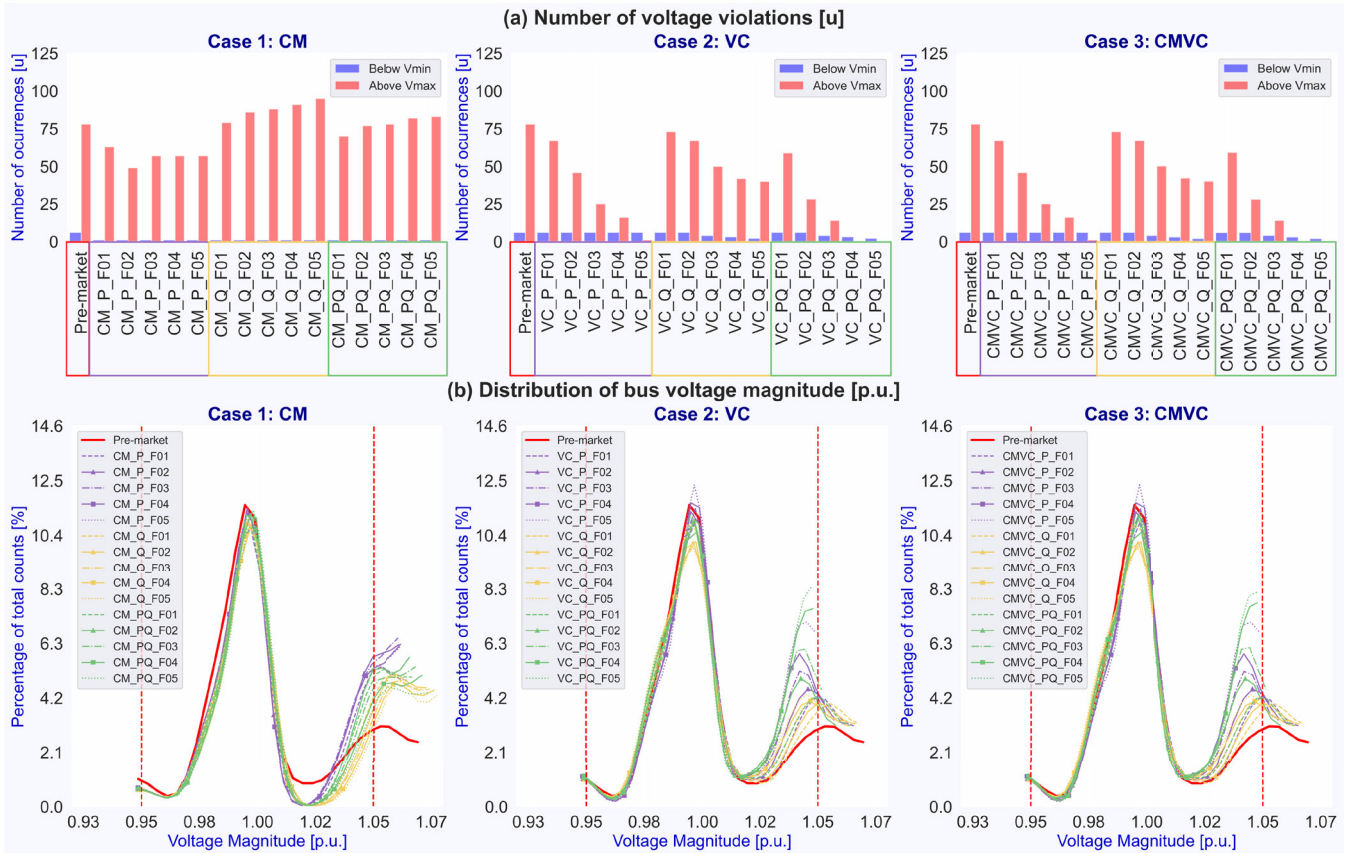


FIGURE 6. Voltage violation indicators comparing the base scenario with the different service-product market designs. (a) Bar plot illustrating the number of voltage violations. (b) Voltage magnitude distribution of all buses [p.u.].

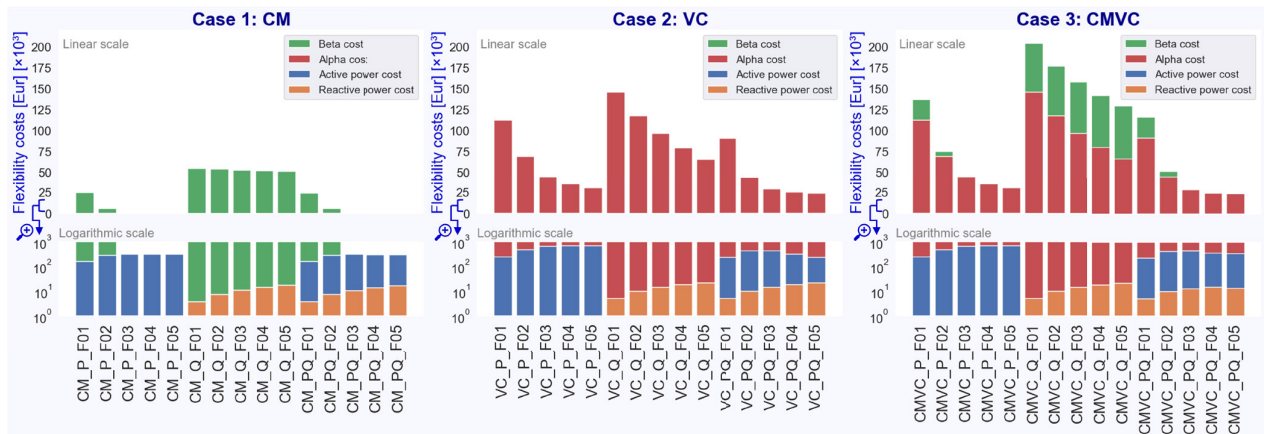
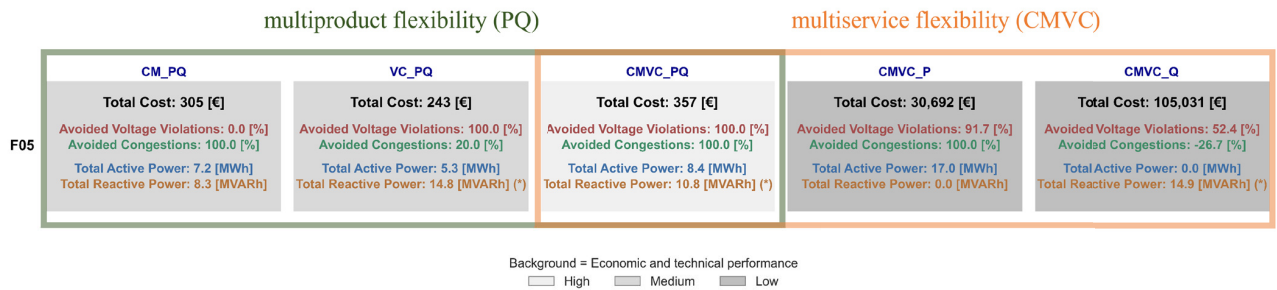


FIGURE 7. Flexibility procurement costs derived from market-clearing results. The upper panels use a linear scale (in thousands of euros,  $\times 10^3 \text{€}$ ). The lower panels display a zoom-in of the same values on a logarithmic scale to highlight lower-cost components.

mitigating almost all network problems, resulting in a significant reduction in penalty costs. As more flexibility volume becomes available, the flexibility procurement costs of P and Q in the CMVC\_PQ can be up to 50% lower than in CMVC\_P. Note that, across all market designs considering more than one product, active power is the dominant cost driver, while reactive power, although less expensive, proves to be technically insufficient. This aspect increases the total costs due to the unmet flexibility need costs.

#### D. MULTI-SERVICE AND MULTI-PRODUCT ASSESSMENT

A technical analysis shows that under-voltage problems persist at bus b3, where sp1 is connected, despite increasing the available flexibility level. The sp1 is connected to a different transformer from the other SPs, which have negligible impact on this bus (sensitivity factors close to zero), while sp1 alone lacks the capacity to fully provide the required flexibility. Given that this study is based on a real Polish demonstrator, the original resource capacities, types and locations were preserved. Thus, the under-voltage



**FIGURE 8.** Comparison of KPIs for multiproduct flexibility (PQ) and multiservice flexibility (CMVC) in F05. Cases marked with (\*) include the 4.022 MVARh required to resolve under-voltage problems.

problems are not related to the LFM design, but rather to insufficient flexibility at bus b3, as no other SPs can provide the required DSO services. As a result, under-voltage problems remain unresolved, distorting the LFM total costs. Therefore, a targeted evaluation was conducted to quantify the flexibility needs associated with under-voltage problems. The results show that this condition is almost exclusively dependent on reactive power, and providing 4.022 MVARh through other procurement mechanisms, such as bilateral contracts (cost potentially linked to the Q costs from the LFM) or targeted rule-based actions (dynamic Q support from DERs, OLTC adjustments, etc.), can alleviate the remaining under-voltage problem at bus b3.

Figure 8 presents the results after incorporating this adjustment, offering a comparison of KPIs for F05, which represents the available flexibility level that yields the best overall results in each market design. The green and orange boxes group the multi-product and multi-service market designs, respectively.

Multi-product (PQ) market designs illustrate the potential of active and reactive power flexibility to address single service objectives. CM\_PQ achieves low costs but fails to solve voltage violations, while VC\_PQ resolves all voltage violations but mitigates only 20% of overloads. Hence, tackling both problems requires operating CM\_PQ and VC\_PQ separately, which is suboptimal due to the higher combined costs and because the two markets are not necessarily aligned to alleviate all network problems.

The multi-service (CMVC) market design also offers technical and economic advantages, as congestion management and voltage control are addressed within a single market-clearing step. Nevertheless, in the present assessment, when only one type of flexibility product is procured, both CMVC\_P and CMVC\_Q prove to be limited. CMVC\_Q is technically insufficient, failing to resolve congestion. CMVC\_P performs better but still leaves some voltage violations unresolved, resulting in high penalty costs.

In contrast, the CMVC\_PQ LFM demonstrates the benefits of co-optimising flexibility products and DSO services, resolving all identified network problems in a more cost-effective manner. Unlike separate single-service (CM\_PQ and VC\_PQ) or single-product (CMVC\_P or CMVC\_Q) designs, CMVC\_PQ achieves the lowest total costs,

with a smaller volume of active and reactive power flexibility. This coordinated approach offers a better trade-off between technical performance and economic efficiency.

## VI. CONCLUSION AND FUTURE RESEARCH

This paper presents a comparative assessment of different LFM service-product market designs for DSO services, analyzing how different combinations of active and reactive power flexibility contribute to congestion management and voltage control in distribution networks within a common AC-sensitivity-based market-clearing framework.

The results of this study reveal that single-product (P or Q) or single-service (CM or VC) LFMs can lead to suboptimal outcomes when multiple network constraints must be addressed simultaneously. Single-product designs do not fully exploit the technical complementarities of flexibility resources. In particular, P-only markets can mitigate most network problems but generally require larger flexibility volumes and lead to higher costs. On the other hand, Q-only markets often fail due to high R/X ratios or limited Q availability. Similarly, single-service markets may overlook network problems beyond their scope (CM for overloads, VC for voltage violations), and solving one can create others, particularly in the absence of pre-qualification processes. Addressing both CM and VC requires running separate markets, which leads to higher costs and may not yield complementary responses.

These findings highlight the value of LFMs that co-optimize multiple flexibility products and DSO services in a single market-clearing step. Active power flexibility is key for overload mitigation, while reactive power, though economical, plays a complementary role in distribution networks for voltage regulation, when properly coordinated. Multi-product LFMs (PQ) result in lower costs than single-product market designs, and by leveraging the complementary effects of P and Q, element overloads and voltage violations can be mitigated simultaneously. Likewise, multi-service LFMs enhance efficiency by jointly considering congestion management and voltage control, avoiding conflicting actions and reducing total costs. Nonetheless, while a joint multi-service and multi-product market offers a comprehensive solution, it may increase the complexity of LFM designs.

Future research should assess whether this added accuracy is justified or if simpler approaches can achieve comparable results under specific network conditions. In this context, the proposed LFM-clearing can be extended from independent single-period to multi-period optimisation that explicitly captures inter-temporal and activation duration constraints, to assess their impact on technical results and flexibility costs over longer horizons (e.g., intra-day and day-ahead). In addition, a formal computational scalability analysis is needed to assess the performance of the proposed AC-sensitivity-based approach in larger, more meshed distribution networks, identifying tractable simplifications, and quantifying their impact on overall results. A comprehensive techno-economic comparison between alternative LFM organisational paradigms, namely DSO-driven flexibility procurement and network-user-driven procurement of network usage rights, together with an assessment of their regulatory implications, represents an important direction for future research building on the modelling framework developed in this work.

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