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Project BeFlexible - When flexibility signals interact: Quantifying the interplay of mechanisms for acquiring DSO services

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Abstract

The growing incorporation of distributed energy resources (DERs), together with the electrification of transport, heating and cooling, is making distribution networks more dynamic and more exposed to local congestion and voltage problems. In this context, system operators are considering a range of flexibility acquisition mechanisms, including network tariffs, local flexibility markets (LFMs), and flexible connection agreements (FCAs), to address these network challenges. However, these mechanisms are often designed independently, even though they can coexist and act on the same customers. Depending on their design and how their signals interact, these acquisition mechanisms may reinforce each other, enabling more effective customer responses to meet network requirements, or, conversely, lead to redundant or conflicting signals that undermine their joint efficiency.

Thus, this work presents a based-model assessment, developed within the BeFlexible project, to analyse how multiple mechanisms for acquiring flexibility interact when implemented jointly in distribution networks with high shares of DERs and flexible demand. The study examines how price signals from network tariffs, local flexibility markets, and flexible connection agreements jointly influence the behaviour of flexible loads, such as electric vehicles (EVs), heat pumps (HPs), and water heaters (WHs), and how these responses translate into network impacts. Four case studies are considered to assess: (i) the interaction between network tariff designs (national and local) and LFMs; (ii) the role of temperature-driven demand variation under these acquisition mechanisms and network impacts; (iii) the effect of changes in regulated tariff components; and (iv) the interplay between FCAs, network tariffs, and LFMs.

The results show that predictable system-wide tariff signals may synchronise flexible demand and unintentionally create local congestion, particularly for highly price-responsive resources. LFMs improve congestion management by introducing locational corrective signals, while ex-post local tariffs help reduce excessive predictability, gaming opportunities, and local market power concentration. Flexible connection agreements further complement tariff- and market-based mechanisms by limiting coincident demand during constrained hours. Overall, the findings highlight that a coordinated acquisition mechanism design is essential to align incentives with local grid constraints, reduce inefficient or conflicting signals, and support the secure and cost-effective operation of active distribution networks.

Introduction

The transition towards decarbonised and electrified energy systems is increasing the complexity of power systems, particularly at the distribution level [1], [2]. The electrification of key sectors, such as mobility and heating, together with the growing integration of decentralised renewable generation, is reshaping traditional demand and generation patterns and altering power flows across electrical grids, increasing the likelihood of congestion and voltage problems [3], [4]. These changes introduce greater variability and uncertainty into network operations and planning, creating new challenges for distribution system operators (DSOs) [3], [5]. However, beyond these concerns, these transitions can also provide opportunities for exploiting the inherent flexibility of power systems [1]. In this context, flexibility is increasingly recognised as a valuable tool to support DSO decision-making, complement conventional network management practices, facilitate the integration of distributed energy resources (DERs), defer or reduce the need for grid reinforcement investments, and improve overall power system efficiency.

To procure flexibility, several mechanisms are currently being developed and implemented across Europe. These mechanisms include network tariffs with time-varying components, local flexibility markets (LFMs), and flexible connection agreements (FCAs) [2], [5], [6]. While these mechanisms pursue similar objectives, they rely on several designs and operational principles and may deliver different signals for customers and flexible service providers. Nevertheless, when they coexist and act simultaneously on the same flexible resources, this may lead to complementary effects, but also to conflicting incentives or inefficient responses if they are not properly coordinated [5].

This work is developed within the Horizon Europe BeFlexible project [5], [7], [8], which aims to facilitate the large-scale integration of flexibility services into electricity distribution networks through coordinated market, regulatory, and technological solutions. The project includes 11 pilots across four European countries (Italy, Sweden, and Spain&France), organised into three demonstrators covering different climatic and operational conditions in Southern, Northern, and Southwestern Europe. These pilots provide real, diverse environments to evaluate flexibility solutions across different network characteristics, regulatory frameworks, and customer behaviours.

This paper presents a first synthesis of the quantitative assessment developed in [8]. The focus is on the interaction between tariff-based signals with LFMs-based activations, and on further joint analysis of these acquisition mechanisms with FCAs-based capacity limitations. The central question concerns how flexibility acquisition mechanisms, beyond their effectiveness in isolation, interact when they coexist and how their joint set of signals impacts flexible resource responses, and translates into technical and economic impacts, in terms of network performance, and flexibility procurement needs and costs.

1. Requirements for Grid Services - Technical & Market Conditions

Flexibility-acquisition mechanisms are becoming increasingly important as electrical grids must accommodate larger and more variable electricity flows. On the demand side, there is growing interest in electrifying end uses, particularly through flexible devices such as electric vehicles (EVs), heat pumps (HPs), and electric water heaters (WHs). In the context of flexibility provision, these types of resources can be strategically employed due to their capability to respond to external signals and adapt their consumption patterns over time. However, high concentrations of these resources in specific local areas may also pose

significant operational challenges for distribution networks. For instance, when large numbers of flexible devices respond simultaneously to the same signal, such as those embedded in network tariffs, their consumption may become synchronised, potentially leading to operational problems [9], including line and transformer overloads and voltage violations across network buses. Table 1 summarises the main characteristics of the flexibility-acquisition mechanisms considered in this work, including the type of signal they provide, key design aspects, and some of the potential operational risks associated with their implementation and interaction with flexible resources.

Mechanism	Main signal	Relevant design dimension	Potential risk
Network tariffs	Price signal (Implicit)	Temporal granularity, spatial granularity, predictability, cost allocation	Synchronised demand shifts; uncertain customer responsiveness
Local flexibility markets	Market activation (Explicit)	Bidding, activation, settlement, liquidity	Residual needs if flexibility volume is limited; Strategic bidding and gaming opportunities
Flexible connection agreements	Capacity limitation (Explicit)	Curtailment conditions, predictability, compensation principles.	Peak reduction may extend consumption over time; secondary peaks; rebound effects.

Table 1. Design dimensions affecting the interaction of flexibility acquisition mechanisms.

The flexibility-acquisition mechanisms considered in this work differ in their operational principles and design dimensions (key characteristics) [5], [8]. Network tariffs are implicit, price-based mechanisms intended to allocate network costs while influencing customer behaviour through economic signals [10]. Across Europe, tariff structures are evolving to better reflect network conditions and incentivise flexibility provision [11], [12], particularly through time-varying components such as time-of-use tariffs. Nevertheless, many existing tariff designs still rely on relatively static, predictable temporal signals, which may unintentionally lead to synchronised customer responses and limit their effectiveness in addressing local network constraints [2], [13].

Local flexibility markets (LFMs) and flexible connection agreements (FCAs), in contrast, are explicit mechanisms for acquiring flexibility [14]. LFMs are market-based procurement mechanisms in which flexibility service providers submit offers that can be activated by system operators to address locational operational needs, such as congestion management or voltage control [15], [16]. Although LFMs are still at different stages of maturity across Europe, several countries and research initiatives are actively developing and testing these mechanisms through pilot projects and demonstrators [17]. On the other hand, FCAs are contractual agreements that define conditional or limited access to network capacity during constrained periods [18]. Under these arrangements, connected users agree to temporary operational restrictions, such as limits on power import or export during network stress conditions, in exchange for faster, more flexible, or lower-cost network connections [19].

These mechanisms are receiving increasing attention as potential alternatives to costly, time-consuming network reinforcements [4], [6], particularly for integrating new demand-side technologies. However, their implementation still faces important regulatory, operational,

and customer-acceptance challenges, particularly regarding the clear definition of roles and responsibilities among stakeholders, the design of fair and transparent activation and remuneration schemes, interoperability and coordination with existing market structures, data exchange and communication requirements, and the need to ensure customer trust and participation [2], [13].

A key assumption behind this analysis is that the coexistence of flexibility-acquisition mechanisms may generate complementarities or conflicts, particularly when they operate uncoordinatedly. For example, a tariff can shift demand away from system-level peak periods, but if large numbers of flexible resources are deployed in a specific area, either through autonomous customer response or coordinated aggregation strategies that react simultaneously to the same predictable low-price signal, local congestion may emerge [20]. Thus, LFMs can procure flexibility to resolve the resulting network constraints. However, inefficient or unfair outcomes may arise if the same resources contributing to the congestion are also allowed to participate in the market to solve the problem they helped create. Moreover, tariff-based signals alone may be ineffective in the presence of local network bottlenecks, where broader system-level incentives do not necessarily reflect local operational conditions. Similarly, flexible connection agreements can help reduce local network stress by limiting the simultaneous use of flexible resources during constrained or critical operating periods. However, overly restrictive limits under predictable baseline conditions may impact the operation of flexible resources, potentially shifting congestion to other time periods, causing rebound effects or secondary peaks. By contrast, activation in less predictable, system-driven conditions, such as contingency or N-1, may reduce opportunities for strategic behaviour and gaming.

2. Interplay and coordination of mechanisms for acquiring DSO services

The proposed approach follows the sequential modelling framework depicted in Figure 1. Harmonised input data are prepared first, including network topology, load and generation profiles, service provider information and acquisition mechanism design parameters. These inputs are used to represent a synthetic MV/LV network and the responses of flexible resources. The flexible resources considered are EVs, HPs, and WHs, as they are price-responsive technologies and can significantly impact local network operations under high-penetration conditions. Together, these resources provide a complementary set of flexibility characteristics for the analysis. EVs mainly respond to price signals; HPs respond to prices while also being constrained by external variables such as ambient temperature, and WHs are additionally affected by hot water consumption patterns and thermal storage dynamics. This diversity is important for assessing how different flexibility-acquisition mechanisms interact under heterogeneous flexibility behaviours and operational constraints.

The first modelling step captures the cost-minimising responses of flexible loads under different network tariff designs. In simplified form, each flexible resource minimises electricity cost by determining its electricity consumption over the considered time horizon, while respecting technical and comfort constraints. For EVs, the constraints include connection windows, battery capacity and state-of-charge requirements. For HPs and WHs, the constraints represent thermal comfort, conversion efficiency, thermal features of building or tank storage, and temperature-dependent demand. In the FCA analysis, EV charging is additionally constrained by contractual maximum power limits.

The second modelling step represents the LFM for congestion management with active power provision (CM-P). In this work, only this type of LFMs has been considered. Other flexibility services and products, such as voltage control service or the procurement of

reactive power (Q) products, which have also been analysed in projects such as EUniversal [21] and OneNet [22], are outside the scope of this study. This simplification is mainly driven by the focus of the considered demonstrators, which only included congestion management services based on active power flexibility. The LFM model minimises the cost of upward and downward active-power flexibility, while satisfying the DSO flexibility needs identified from the power-flow analysis. The flexibility needs are determined by validating each load profile through power-flow simulations, during which line and transformer overloads and voltage deviations are identified. The resulting configurations are evaluated through KPIs covering congestion reduction, remaining flexibility needs, voltage violations and cost impacts.

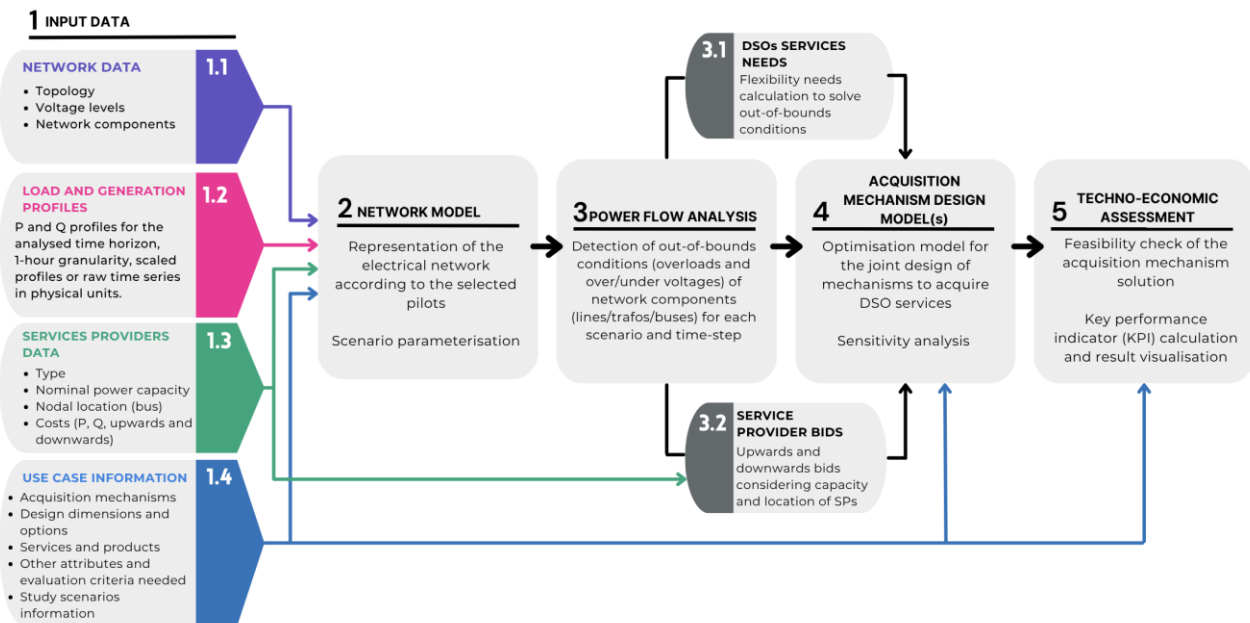


Figure 1. Sequential modelling framework for combined acquisition mechanism designs.

This sequence is designed to capture feedback and interdependence across different flexibility acquisition mechanisms. First, the model identifies the demand profiles resulting from the combined effect of system-wide tariff signals and, when applicable, FCA constraints imposed on flexible resources. Secondly, the LFM quantifies the flexibility procurement required to resolve the local grid constraints created by these responses. The framework, therefore, enables the assessment of how tariff-based incentives, market-based flexibility activation, and contractual capacity limitations interact under realistic operating conditions.

3. Case studies and assessment framework

Four case studies are developed to isolate the effect of different design dimensions under comparable network conditions, as shown in Table 2. Cases 1 to 3 focus on the interaction between tariff-based signals and LFM activations. Case 4 extends the analysis to FCA. The same simplified synthetic network is used across cases to avoid attributing changes in performance to different grid topologies rather than to the acquisition mechanism design.

In this work, global tariffs refer to country-level electricity tariffs that provide system-wide price signals to consumers, typically through time-dependent or volumetric tariff structures. Local tariffs are introduced as ex post corrective signals derived from local congestion conditions assessed during an LFM clearing step, with the objective of reducing synchronised demand responses and better reflecting local network constraints. By introducing locational and less predictable signals, ex-post local tariffs aim to reduce the

excessive predictability associated with global tariffs, which may otherwise encourage strategic behaviour, synchronised responses, gaming opportunities, or local market power concentration. The LFM is used to procure active-power flexibility from DERs to mitigate residual network problems identified after responding to tariff signals. The coordinated use of LFMs and ex-post local tariffs is particularly relevant under conditions of limited flexibility availability. Correspondingly, FCAs impose contractual operational limits on flexible resources, particularly EV charging, during constrained periods to directly adapt their consumption to local network conditions. A detailed description of the modelling and simulation process can be found in Deliverable D7.1 of the BeFlexible project [23].

Case	Network model	Electricity price	Temperature	Acquisition mechanisms	Purpose
Case 1: Impact of network tariff designs	Same for all	Spain (time blocks)	Same for all	Global tariff + LFM + ex-post local tariff	Compare time-block, flatter and volumetric tariff designs under identical operating conditions
		Italy (flatter tariff)			
		Sweden (volumetric)			
Case 2 Temperature-driven demand variation		Spain (time blocks)	Spain	Global tariff + LFM + ex-post local tariff	Assess whether temperature changes modify the structural interaction between tariffs and LFMs
		Italy (flatter tariff)	Italy		
		Sweden (volumetric)	Sweden		
Case 3 Impact of tariff taxes		Spain (time blocks)	Spain	Global tariff (without charges) + LFM + local tariff	Evaluate how changes in system charges affect DERs behaviour and grid constraints
Case 4 Flexible connection agreements		Sweden (volumetric)	Sweden	Global tariff + FCA + LFM	Analyse the coordinated operation of tariffs, LFMs, and flexible connection agreements

Table 2. Case studies used to assess the interaction of flexibility acquisition mechanisms

4. Results and Discussion: Network Tariffs + LFM

The results show that tariff design is a dominant driver of flexible-resource responses. Predictable national tariff signals can lead to many price-responsive loads shifting consumption into the same low-price periods. This effect is particularly relevant for concentrated, flexible resources with relatively high-power requirements, whose operations are strongly influenced by the network tariff signal. Under these conditions, a tariff intended to reduce system-level costs may unintentionally generate local congestion in areas with high DER deployment. The assessment also shows that, under the analysed network conditions, preheating capabilities represented in the optimisation model reduce the direct effect of temperature on HPs and WHs, making price signals the main driver of DER responses. Although different regional temperature profiles were analysed to represent distinct climatic conditions, temperature primarily increases overall electricity consumption and may amplify the magnitude of overload and voltage problems, rather than substantially modifying their temporal patterns. In most cases, the synchronisation of flexible-resource

responses continues to be primarily driven by tariff signals, since flexible resources remain strongly concentrated around predictable low-price periods. As a result, temperature mainly scales the severity of the impacts, which may require greater flexibility, whereas network tariff design determines when and how those impacts appear in the network.

Furthermore, when the LFM is applied after the tariff-driven response, congestion can be reduced as flexibility availability increases. In the developed assessment, the combined tariff + LFM configuration reduces congestion by approximately 15-77%, depending on the tariff design and the available flexibility volume. However, the results also show that the LFM may be insufficient when synchronisation is strong and local flexibility available is limited. This highlights the potential value of coordinating LFMs and network tariff design.

The introduction of an ex-post local tariff improves interaction for solving local network constraints under limited flexibility. Its role is to complement the national tariff and LFM, translating electricity costs into a less predictable, more locationally targeted signal. This reduces the risk that all flexible resources react in the same way to a fully predictable national tariff design. In the simulations, the combination of tariffs, LFM, and ex-post local tariffs fully resolves congestion in the analysed configurations, achieving 100% congestion resolution.

Additional sensitivity analyses on regulated system charges within time-block tariffs indicate that modifications in these tariff components can reshape flexible-resource responses and interact with local corrective mechanisms. This highlights the need to assess tariff modifications jointly with local flexibility mechanisms.

Nevertheless, two limitations are important. First, if the corrective local signal becomes predictable, it can create new synchronisation patterns and shift problems to adjacent hours. Second, the LFM model in this analysis focuses on active-power congestion management. As a consequence, congestion-oriented measures do not fully solve voltage-related problems. The results indicate that active-power-only mechanisms solve only part of the voltage problems, with voltage-problem resolution ranging from 1.29% to 55.06%. This reinforces the need to complement congestion management with voltage-control services, including reactive-power products or other voltage-targeted mechanisms.

5. Results and Discussion: Network tariff + LFM + FCA

Flexible connection agreements provide a more direct network-driven signal than network tariffs. Instead of relying only on price response, they impose a maximum operating limit during constrained periods or under specific network conditions. In the case analysed, FCAs are applied only to EV charging. This is a relevant application because EV demand is both flexible and potentially highly coincident, especially when many users respond to the same tariff incentives.

The coordinated design of FCAs with the LFM produces strong improvements. The final-event synthesis reports congestion reductions between 46.51% and 100% when both mechanisms are coordinated. In addition, total costs decreased by 67.14-98.8% compared with the tariff + LFM baseline. These results indicate that contractual capacity limits can reduce the amount of flexibility required through the LFM, lowering congestion-management costs and increasing the effective hosting capacity of the network.

However, the results also show that contract design is critical. Moderately restrictive limits reduce instantaneous EV charging peaks and therefore help prevent overloads. Overly restrictive limits can have the opposite effect: they reduce charging power but increase

charging duration, causing many EVs to continue charging in later periods. If this delayed charging becomes synchronised, congestion is shifted rather than solved. In this context, the predictability of FCA activation conditions also becomes relevant. Highly predictable capacity restrictions may lead to synchronised or strategic behavioural responses, while activation linked to less predictable, more system-driven conditions, such as contingency or N-1 situations, may reduce the likelihood of rebound effects and gaming opportunities. These results reinforce that FCA effectiveness depends on how curtailment conditions are defined and coordinated with other flexibility-acquisition mechanisms.

6. Added Values and Conclusions

The analysis confirms that the mechanisms for acquiring flexibility for DSO services cannot be considered in isolation. Their effects are assessed by the responses of flexible resources, and the same resource may simultaneously respond to tariff signals, market opportunities and contractual capacity limits. Coordinated design is therefore essential to avoid conflicting incentives, rebound effects and inefficient flexibility procurement.

- Predictable system-wide tariff signals are a key driver of synchronised demand response. They can reduce costs for customers, but may create local congestion when a high concentration of flexible resources clusters in the same low-price windows in a specific area.
- LFM provides an effective corrective mechanism, but their performance depends on available flexibility volumes and the demand responses driven by tariff signals. The LFM should therefore be aligned with explicit knowledge of tariff limitations to avoid inefficient situations in which the LFM is used to mitigate network problems caused by tariff-driven responses.
- Ex-post local tariffs can complement limited global tariff designs by introducing more locational and corrective signals. They may improve cost causality and reduce gaming risks, though their effectiveness depends on maintaining sufficient uncertainty to avoid creating additional predictable synchronisation patterns.
- FCAs can complement tariffs and LFMs, particularly under high DER deployment and limited flexibility availability, by reducing simultaneous demand peaks and lowering the need for corrective flexibility procurement. However, FCA design conditions should carefully evaluate the signals sent to flexible resources, since overly restrictive or highly predictable curtailment conditions may shift congestion. These results reinforce the importance of coordinating FCAs, network tariffs, and LFMs within an integrated flexibility acquisition.
- Active-power congestion management alone is not sufficient to solve all network problems. Voltage deviations require complementary voltage-control services or products.

For stakeholders, regulators and DSOs, the main implication is that flexibility mechanisms should be coordinated across temporal granularity, spatial granularity, and contractual and activation conditions. A well-designed portfolio of flexibility acquisition mechanisms can increase hosting capacity and reduce the need for network reinforcement, while a poorly coordinated portfolio can shift problems across time periods, network elements, or mechanism layers. Future work should extend the framework to include uncertainty, additional voltage-control services and products, strategic bidding behaviour and a broader range of network configurations.

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