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Local flexibility markets in Europe: A critical review of market designs, operational maturity and stakeholder perspectives

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A B S T R A C T

Local Flexibility Markets (LFMs) are gaining importance across Europe as a potential solution to emerging challenges in the management of distribution networks. Driven by European Union directives on electricity market design, LFMs aim to enable distribution system operators to procure ancillary services from distributed energy resources through transparent and economically efficient mechanisms. This study offers a comprehensive analysis of the designs and current implementation stages of LFMs, combining a systematic literature review with an in-depth assessment of selected European cases and structured interviews with key stakeholders. The literature analysis highlights current research trends, methodological approaches, and future developments. The case analysis covers various European countries, including nations with mature LFMs, such as Great Britain, as well as those where LFMs are still in the early stages of development, such as Italy. Specifically, it provides detailed insights into ancillary services definitions, technical and market requirements, remuneration schemes, baseline calculation methodologies, and observed market outcomes. Interviews with distribution system operators, balancing service providers, and market platform operators enrich the analysis by revealing practical perspectives on the benefits and challenges of LFMs. The findings indicate that regulatory fragmentation, lack of standardized flexibility products, and inadequate communication and automation infrastructure are major barriers to broader deployment. Unlocking the full potential of LFMs will require coordinated regulatory action at the European level and targeted investments in essential enabling technologies.

Glossary.

API	Application Programming Interface
ASM	Ancillary Services Market
BESS	Battery Energy Storage System
BRP	Balance Responsible Party
BSP	Balancing Service Provider
DER	Distributed Energy Resource
DERMS	Distributed Energy Resource Management System
DG	Distributed Generation
DR	Demand Response
DR NC	Network Code on Demand Response
DSO	Distribution System Operator
EC	Energy Community
EFA	Electricity Forward Agreement
ENA	Energy Networks Association
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
GB	Great Britain
GME	Gestore Mercati Energetici
HP	Heat Pump
HV	High Voltage
ICT	Information and Communication Technology
IoT	Internet of Things
LFM	Local Flexibility Market
LV	Low-Voltage
MPC	Model Predictive Control
MPO	Market Platform Operator
MV	Medium-Voltage
OU	Operational Utilisation
PGUI	Power Guide User Interface
PLC	Programmable Logic Controller
PR	Peak Reduction
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
PV	Photovoltaic
P2P	Peer-to-Peer
RES	Renewable Energy Sources
SA	Scheduled Availability

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SCADA	Supervisory Control And Data Acquisition
SU	Scheduled Utilisation
TSO	Transmission System Operator
VPP	Virtual Power Plant
VA	Variable Availability
V2G	Vehicle-to-Grid

1. Introduction

The ongoing energy transition in Europe is leading to the decentralization of power generation, with a growing number of medium- and small-scale production units connected to Medium Voltage (MV) and Low Voltage (LV) distribution grids. This shift is mainly driven by the widespread deployment of Renewable Energy Sources (RES), as well as by policy efforts aimed at promoting prosumer engagement [1] and community-led initiatives in the energy sector [2]. This trend is particularly evident in the case of photovoltaic (PV) power plants: as of 2024, Europe recorded an additional 65.5 GW of newly installed PV capacity, bringing the total to 338 GW, with distributed installations accounting for 58 % of the overall capacity [3]. At the same time, the electrification of final energy consumption is accelerating, primarily driven by Heat Pumps (HPs) and Electric Vehicles (EVs) [4]. HPs are the leading solution for decarbonizing building climate control, with over 2 million units installed in Europe in 2024 [5], while EVs play a crucial role in the transport sector's decarbonization, with approximately 10 million vehicles purchased in Europe between 2013 and 2023 [6]. Furthermore, sector coupling is also gaining importance in industry. Although in recent years electrification of industrial energy demand has stagnated at around 33 % [7], it is expected to accelerate under the European Commission's Clean Industrial Deal, which seeks to boost electrification in energy-intensive processes such as iron and steel production, chemicals, and cement [8].

Both distributed PV systems and controllable loads such as EVs and HPs fall under the category of Distributed Energy Resources (DERs). As defined by the European Commission [9], DERs encompass Distributed Generation (DG), Energy Storage Systems (ESS) and Demand Response (DR) resources connected to MV and LV networks, as represented in Fig. 1. DERs can offer several benefits, such as reducing energy costs [10], enhancing resilience by providing backup power during outages [11], and enabling prosumers to better align consumption with production [12]. They also support decarbonization by reducing reliance on fossil fuels [13]. However, their rapid growth poses challenges for distribution networks, including voltage and thermal limit violations, grid congestion, and low-inertia issues [14]. Addressing these problems requires substantial grid upgrades [15], which can be limited by space and permitting constraints, especially in dense urban areas [16], and may lead to higher grid-related costs, possibly representing sub-optimal and cost-inefficient solutions from a societal perspective [17].

Given these aspects, relying exclusively on traditional grid reinforcements may no longer represent the most effective strategy for addressing challenges in distribution networks. One possible measure is the revision of grid codes to require DG units to incorporate advanced inverter functionalities, such as the capability to withstand voltage and frequency transients (i.e., voltage/frequency ride-through) [15]. For instance, through advanced control schemes such as volt-var droop characteristics and constant power factor modes, inverter-based DERs have the ability to inject or absorb reactive power to maintain voltage within the acceptable limits [18]. Another measure involves adopting flexible grid connection arrangements, which enable the connection of new DERs in congested areas of the grid, limiting the export or import capacity of the connected units during critical periods for the distribution network [19]. These contracts can be implemented either as long-term alternatives to conventional reinforcements or as temporary measures to defer necessary infrastructure upgrades.

Finally, building on the established framework for procuring flexibility services at the Transmission System Operator (TSO) level [20], a solution is the development of Local Flexibility Markets (LFMs), in which DSOs can directly acquire ancillary services from DERs [21]. These markets are key to reducing the costs of energy transition, particularly by unlocking demand-side flexibility, which is a historically underutilized but highly cost-effective resource [22]. While traditional centralized power systems made limited use of DR, this is now increasingly vital due to the limited dispatchability of renewable generation and the rising need for flexibility across the system [23].

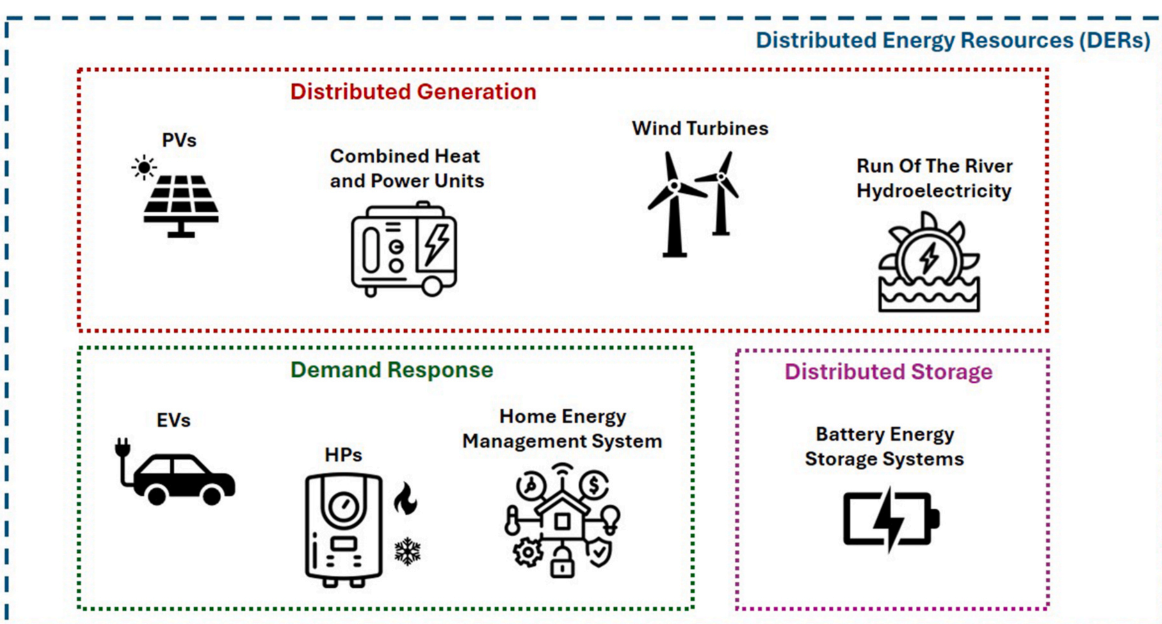

Fig. 1. Graphical representation of DERs.
According to the European Commission, DERs encompass distributed generation technologies such as photovoltaics and wind turbines, distributed storage systems like battery energy storage, and flexible demand-side resources including electric vehicles and heat pumps, capable of providing demand response services.

Moreover, LFMs can accelerate the integration of non-dispatchable RES by addressing local grid congestions, enabling the faster connection of new installations [24].

1.1. Overview of local flexibility market initiatives in Europe

In this article, we adopt the definition of *Local Flexibility Markets (LFMs)* provided in Refs. [24,25], referring broadly to all market-based mechanisms through which DSOs procure flexibility services, regardless of their design (e.g., real-time markets or long-term tenders) or implementation stage (e.g., pilot projects or fully operational schemes). DERs participating in these markets are typically managed by Balance Service Providers (BSPs), as defined in the European Guideline on Electricity Balancing [26], which identifies BSPs as market participants responsible for managing units qualified to deliver flexibility services.

The first European initiatives regarding LFMs emerged in Great Britain (GB) and the Netherlands, where these markets are now among the most advanced in Europe. In December 2018, following various consultations and pilot tests, all six British DSOs signed the Flexibility Commitment promoted by the Energy Networks Association (ENA) [27], pledging to integrate local flexibility services into distribution network operations, as an alternative to grid reinforcement whenever it proves to be the most efficient solution. Around the same time, the Netherlands launched the GOPACS platform [28], enabling the TSO and DSOs to acquire services for congestion management on their networks. Due to these initiatives, the topic gained attention at the European Union (EU) level, resulting in the EU Directive 944 of June 5, 2019 [29], which urged all member states to establish a regulatory framework that allows and incentivizes DSOs to procure flexibility services from DERs. Specifically, Article 31 of the same directive mandates that DSOs must acquire these services in a non-discriminatory and transparent manner through market-based mechanisms, except in cases in which the national regulatory authority determines that a market-based approach is not economically efficient and grants an exemption. Moreover, the directive requires that the procurement of flexibility services follows the principle of technological neutrality, including all potential BSPs connected to the distribution grid. Finally, it highlights the need for local markets to be integrated with the global markets managed by the TSO to ensure efficient and coordinated procurement.

Following these guidelines, several further LFM initiatives have been launched across Europe. In France, in 2020, the DSO Enedis introduced the first long-term market auction for acquiring active power regulation services [30]. That same year, in Sweden, the *Sthlmflex* project was launched to procure local flexibility during winter, when high electricity demand for heating creates significant critical conditions on the distribution grid in the Stockholm region [31]. In Italy, ARERA, the Italian Energy Authority, incorporated the instructions of Directive 944 through Resolution 352/2021 [32], initiating pilot projects for the creation of LFMs by DSOs. In August 2023, two projects were approved, each with distinct regulatory structures: *EDGE* [33], developed by E-Distribuzione, which follows a forward market structure, and *RomeFlex* [34], designed by Areti with support from GME (Gestore dei Mercati Energetici), which combines both forward and spot market mechanisms. In April 2024, a third pilot project, *MiNDFlex* [35], was launched by Unareti, adopting a market structure similar to *RomeFlex*. Similarly, in Portugal, in 2023, the DSO E-Redes started the *FIRMe* [36] project, conducting its first auctions for service procurement in July of the same year. Finally, in Slovenia, Elektro Ljubljana, the DSO for the capital city, launched its first call in 2023 to procure flexibility services from users connected to LV networks [37].

1.2. Contributions of the work and novelty

Building on the regulatory fragmentation observed across countries, several studies review how DER flexibility can be procured and which instruments best serve DSOs. Table 1 synthesizes prior work, indicating for each study the LFM dimensions covered and the perspective adopted. Gulotta et al. [40] take a broad view of the drivers and barriers to integrating DERs into ancillary service markets (ASMs). The review outlines required regulatory updates, the optimization tools needed for planning and controlling DER portfolios, and the technological advances necessary to make DERs flexibility practically exploitable. LFMs are mentioned only briefly, as one of several regulatory innovations the EU should consider to expand the role of DERs in flexibility provision. Jin et al. [38] present a comprehensive review of existing literature analyzing LFMs across four high-level dimensions: concepts and definitions, operational challenge solutions, market formulations, and clearing mechanisms. This review emphasizes the importance of scalable and adaptable market designs, coordination between LFMs and central markets, and the use of decomposition and bi-level optimization for clearing processes. Similarly, Rebenaque et al. [41] review the scientific literature on local flexibility and examine implemented commercial platforms (e.g., Cornwall LEM, Piclo Flex, IREMEL) alongside pilot projects (e.g., InterFlex, Enera). The study identifies four non-technical challenges to successful LFM implementation: governance models, TSO–DSO coordination, *inc–dec* gaming, and entry barriers. Based on the analyzed case studies, the authors propose practical countermeasures for each. Frontier Economics' report for ENTSO-E [25] moves from high-level discussion to a comparative assessment of operating flexibility platforms. It examines how emerging platforms coordinate procurement, trading, and service activation by DSOs and TSOs, analyzing eight real-world implementations (e.g., GOPACS, Piclo Flex, NODES). The key findings highlight the central role of aggregators, the need for effective TSO–DSO collaboration, and the challenge of harmonizing product definitions and market designs across Europe. Similarly, Valarezo et al. [39] analyze trends in new flexibility markets by comparing a wide set of market and aggregator platforms across Europe using a common template (market description, structure,

Table 1
Taxonomy of prior reviews on DER flexibility and LFMs.

Ref.	Description	Year	Scientific research insights analyzed?	LFMs specifications presented and compared?	LFMs results/ maturity presented?	Stakeholder perspectives?
[40]	Literature review on opening ASM to DERs	2023	✓	x	x	x
[38]	Literature review on LFMs focusing on market models and clearing methods	2020	✓	x	x	x
[41]	Analysis of four barriers to LFMs success: governance issues, TSO/DSO coordination, Inc-Dec gaming, entry barriers	2023	✓	x	x	x
[25]	Report on flexibility platforms in Europe	2021	x	✓	x	x
[39]	Analysis of new flexibility markets and aggregator models in Europe	2021	x	✓	x	x
[42]	Review of LFMs in Europe focusing on product definition	2025	x	✓	x	x
[43]	Review of a large number of LFMs to assess their features and challenges	2023	✓	✓	x	x
[24]	Report on LFMs in Europe	2022	x	✓	✓	✓

timing). They conclude that the new models are technically and economically justified to enable DSO flexibility procurement (primarily for congestion management), and they stress the importance of integrating these mechanisms with wholesale and balancing markets. Jimeno et al. [42] focus on LFM products, comparing definitions across national contexts and reviewing recent developments in the UK, France, the Netherlands, and Norway, as well as pilots in Italy and Spain. They document heterogeneity in product design and different approaches to baseline verification. Key challenges individuated by the study include enabling broader participation of small-scale DERs, improving validation of service provision, and extending LFM scope beyond congestion management. Viganò et al. [43] expand the picture with a comprehensive review of more than 70 scientific references and 65 European pilots, comparing real LFM designs and assessing how local flexibility is treated in the literature. The analysis focuses on TSO–DSO coordination, procurement time horizons, and baseline methodologies. Key findings are that DSO congestion management via periodic, pay-as-bid auctions is the dominant practice, and that baseline precision deteriorates for smaller, more variable DER aggregations. Barriers are grouped into technical, economic, and regulatory categories, highlighting the need for harmonized standards and incentives. Finally, Chondrogiannis et al. [24] offer evidence-based support for European policy by reviewing LFM status and design across six countries through desktop research, case studies, and interviews. They analyze selected LFMs along five dimensions (pre-qualification, product design, trading, activation, settlement), showing heterogeneity in product design and baselining methodologies, as well as persistent TSO–DSO coordination issues. The UK and the Netherlands emerge as case studies with mature LFMs, while France, Norway, Sweden, and Germany show mixed or pilot-stage experiences.

As Table 1 shows, prior studies have offered extensive reviews of DER-based flexibility, either through literature syntheses or by examining real-world experiences across countries. However, a complete description of the dimensions along which research on local flexibility is progressing is still missing. Likewise, a current, concrete picture of European LFMs—covering market platforms, product definitions, activation methods, economic settlement and baselines, and market outcomes (e.g., prices, liquidity)—is lacking. Although reference [24] provides something similar, it is limited to 2022, while several initiatives have since emerged or changed substantially. Finally, none of the surveyed studies offers a clear, actor-differentiated account of stakeholder views on future LFM development. While [24] includes interviews, the findings are mainly used to describe case characteristics and to list suggested improvements, rather than to compare viewpoints across stakeholders.

Our study addresses these gaps. We provide a single, updated review that consolidates all elements summarized in Table 1. First, we conduct a PRISMA-guided bibliometric analysis of academic databases to map which aspects of DER flexibility are most frequently addressed in the literature. Building on this, we analyze practical implementations across European countries, comparing local procurement approaches. To map market structures, we rely on publicly available information from key stakeholders' websites. The LFMs included are selected to capture the breadth of design options and degrees of maturity. Beyond this mapping, we collect first-hand perspectives from DSOs, BSPs, and market platform operators (MPOs) through interviews, organizing their views by actor to reveal convergences and divergences. The adopted methodology, described in detail in the following sections, is summarized in Fig. 2.

In summary, the novelty of this work lies in an updated synthesis of LFMs that *i)* analyzes current research directions on the topic, *ii)* quantifies differences in market design and outcomes across selected European LFMs, and *iii)* structures stakeholder insights (DSOs, BSPs, MPOs) in a comparative manner. By combining quantitative evidence and qualitative perspectives, the review offers a concise, policy-relevant understanding of Europe's evolving LFM landscape.

This paper is structured as follows. Section 2 presents a systematic literature review on local ancillary services provided by DERs. Section 3 summarizes some of the key LFMs currently active in Europe, highlighting their differences, limitations, and potential future

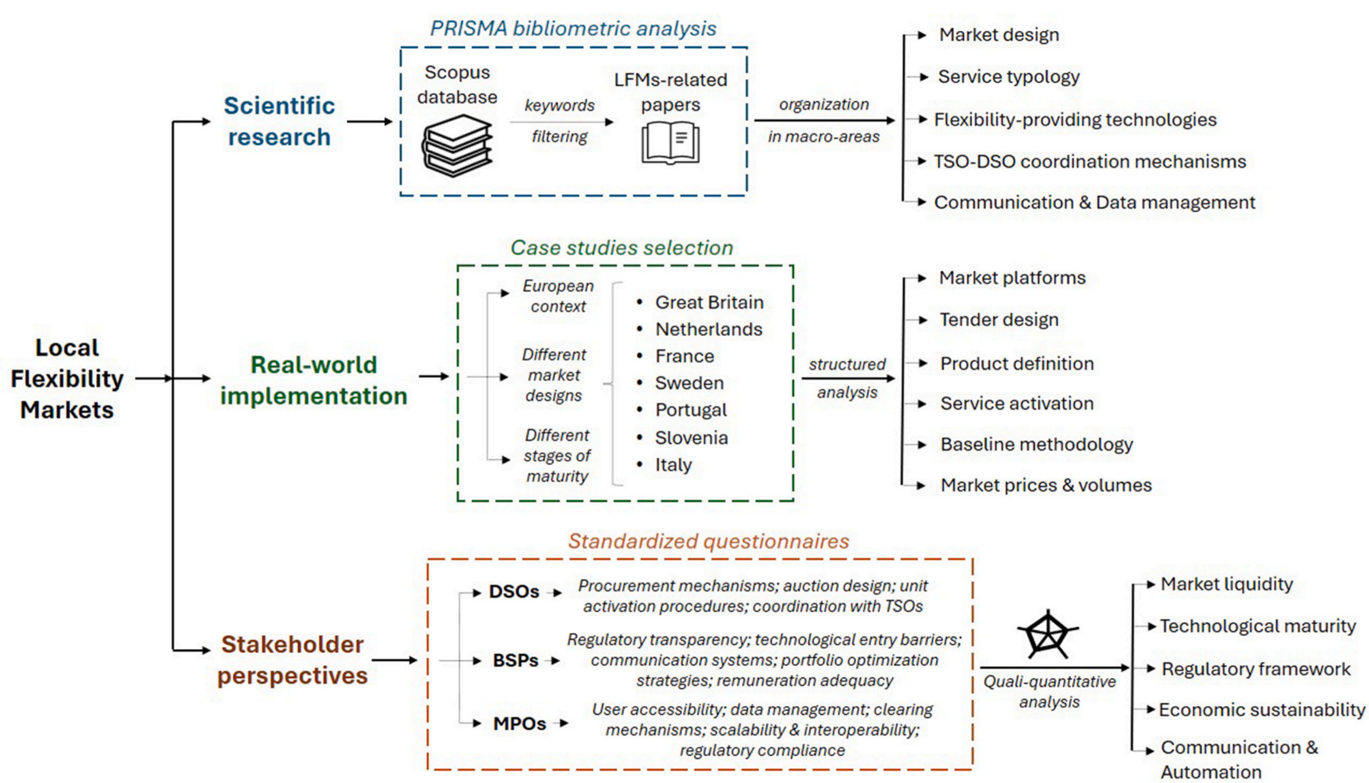

Fig. 2. Conceptual methodology diagram.
LFM dimensions assessed, inputs (reviewed literature, analyzed case studies, stakeholder interviews), analytical procedures, and integrated outputs.

developments. Section 4 presents the results of interviews conducted with DSOs, BSPs, and MPOs involved in some of the analyzed projects. Finally, Section 5 offers the conclusions of the study, emphasizing regulatory and policy lessons learnt.

2. Literature analysis on local flexibility markets based on bibliometric data

In recent years, the growing penetration of DERs has heightened the need for localized, market-based solutions to address grid congestion, ensure voltage control, and support real-time balancing at the distribution level. In this context, LFMs have gained attention as a promising option, attracting increasing academic interest and a growing body of literature on their design and implementation [44]. This section provides a comprehensive and systematic review of the current research on LFMs, mapping the field's thematic evolution, identifying key trends, and offering a structured overview of LFM's main features.

First, to assess the evolution of research in LFMs, a bibliometric analysis was conducted on publications from the past decade (2015–2024). The methodology follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [45], ensuring a transparent and replicable approach. An initial selection of 36′537 references was extracted from the *Scopus* database based on their potential relevance, encompassing a broad set of keywords related to the topic of interest, such as *virtual power plant (VPP)*, *distributed energy resources*, *distributed generation*, and *aggregator*, among others. The database queries were structured using logical operators (e.g., AND/OR), and the metadata were thoroughly reviewed to exclude irrelevant results.

Fig. 3 presents the annual distribution of publications related to LFMs from 2015 to 2024. Among the published works, 47.7 % are journal papers, 49.6 % conference proceedings, and 2.7 % book chapters. The number of publications has more than doubled over the past decade, reflecting the increasing interest in LFMs, in line with the guidelines set out in the EU Electricity Market Directive [29], and supported by various scientific reports [24,46,47].

Building on the initial set of references, the bibliometric analysis was further refined by defining five thematic macro-areas, identified by the authors as the most relevant dimensions of research related to the development of LFMs. For each macro-area, the authors defined a set of relevant keywords to capture all scientific publications specifically addressing that aspect of LFM research. The level of academic interest in each macro-area is illustrated in the bar chart shown in Fig. 4. Each bar represents the share of publications in the initial database that include at least one keyword associated with the respective thematic area. The five macro-areas are as follows.

- *Market Design*: focusing on the regulatory frameworks, pricing mechanisms, and market structures to enable procurement of services by DERs.
- *Service Typology*: referring to the classification of flexibility services provided by DERs.
- *Flexibility-providing Technologies*: investigating which DERs are utilized to provide flexibility services.
- *TSO-DSO Coordination Mechanisms*: addressing the strategies for coordination between TSOs and DSOs in procuring and activating flexibility.
- *Communication Infrastructure and Data Management*: focusing on the digital platforms, communication protocols, and data governance models of LFMs.

The analysis indicates that technical solutions are the most commonly explored topic in the literature, followed by research on the services provided by DERs and communication infrastructure. In contrast, market design and TSO-DSO coordination mechanisms receive considerably less attention, at least among the studies selected after the initial filtering. The following sections provide a detailed overview of each macro area, outlining key themes and insights.

2.1. Market design

To better understand how the market design macro-area has been addressed in the literature, the associated keywords were grouped into subcategories: *market timescale*, *market mechanism*, *local energy communities*. This allows a more structured analysis of the key topics addressed in the literature, facilitating the organization of the relevant studies. The relative importance of each subcategory is illustrated in the pie chart in Fig. 5, with the corresponding keywords listed alongside, ensuring the reproducibility of the research. The same approach is applied in the following subsections for the remaining macro-areas.

The *market timescale* subcategory is addressed in 37 % of the papers analyzed, reflecting an ongoing debate about the advantages of

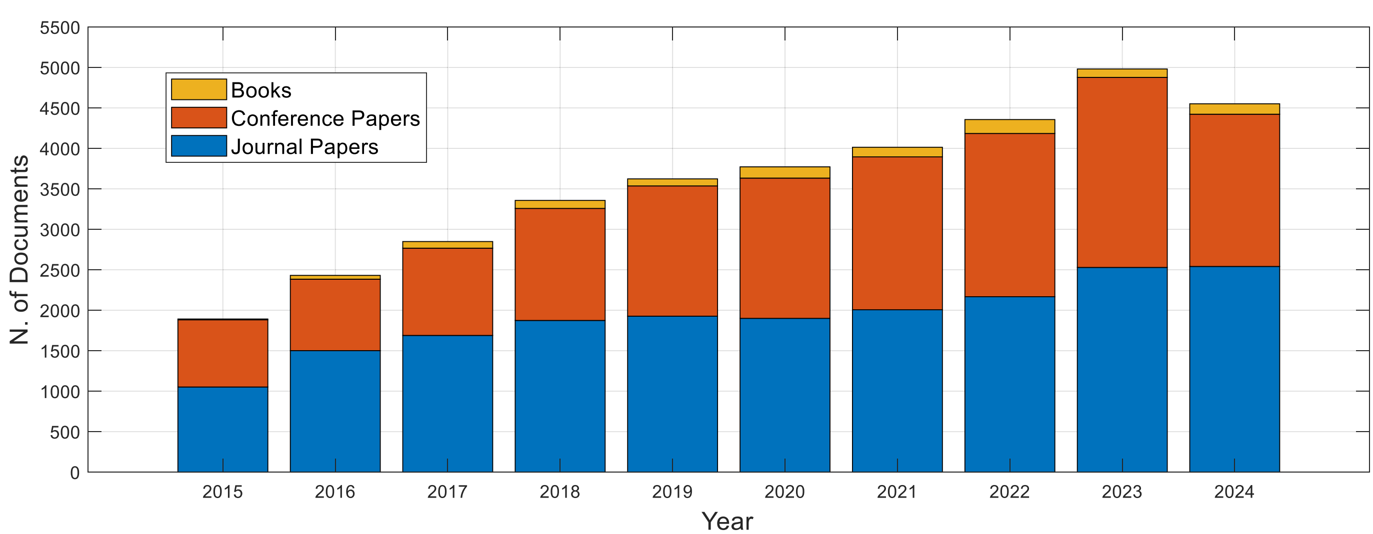

Fig. 3. Annual publication trends on LFMs, 2015–2024.
Vertical bars represent the yearly number of publications, with colors indicating publication type: yellow for book chapters, red for conference papers, and blue for journal articles. The number of publications addressing LFM topics has more than doubled over the past decade. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

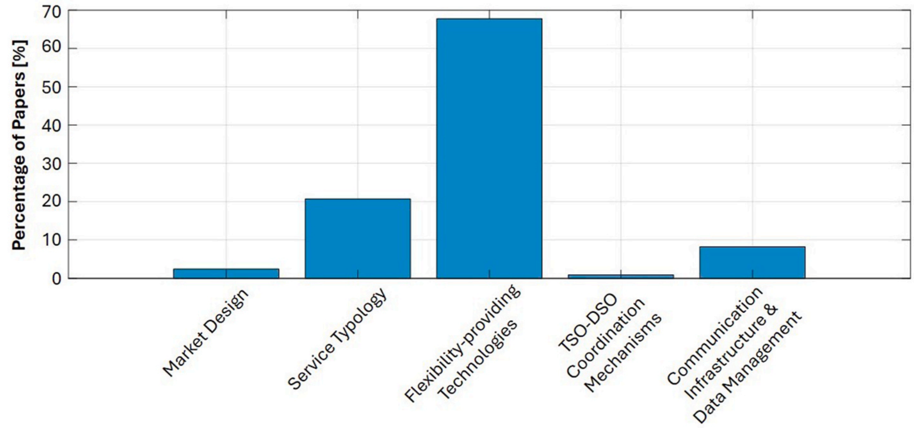

Fig. 4. Distribution of publications by thematic macro-area in LFM research.
Each bar indicates the proportion of publications addressing one of five key research areas in LFMs, identified through keyword-based filtering. The majority of studies focus on specific DER technologies providing flexibility services, whereas topics related to TSO–DSO coordination are the least explored.

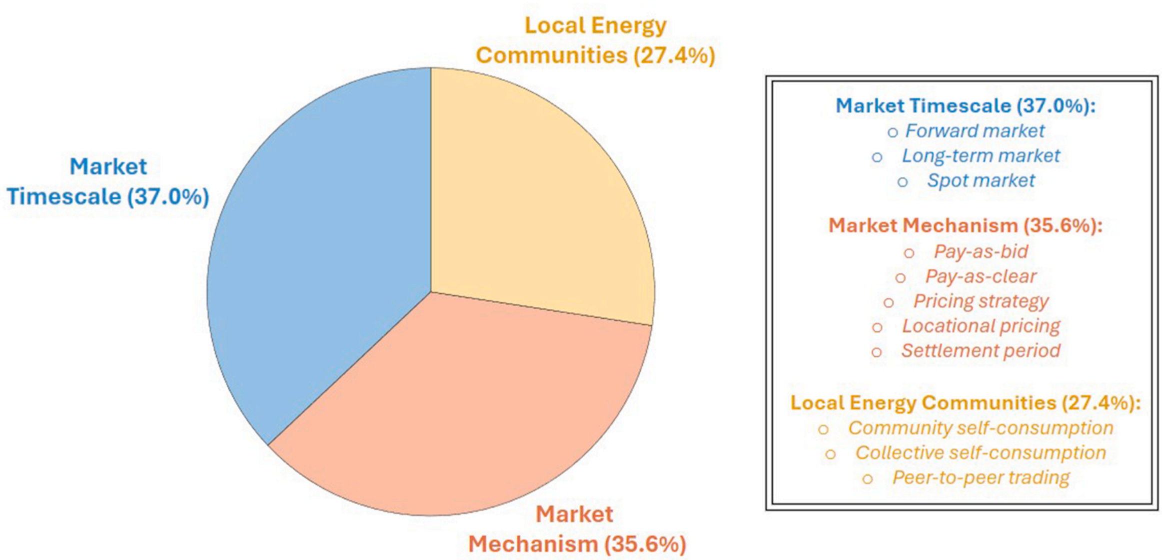

Fig. 5. Breakdown of the market design macro-area into thematic subcategories.
The pie chart shows the relative share of publications addressing each subcategory within the market design dimension. Keywords associated with each subcategory are listed alongside.

procuring flexibility in the short term versus the long term. Several studies advocate forward market structures. Ziras et al. [48], for instance, propose a two-stage, uniform-pricing auction (yearly and monthly) that effectively reduces DSO costs by leveraging unused EV charging capacity. Lustenberger et al. [49] emphasize the importance of securing flexibility commitments at least one year in advance, allowing DSOs to assess the cost-effectiveness of local flexibility services procurement compared to traditional grid reinforcement. The proposed approach relies on trading clearly defined long-term capacity limitation products, which address the shortcomings of spot markets by leveraging on greater reliability and liquidity. Nolden et al. [50] further indicate that current short-term LFMs generate transaction costs that often outweigh revenues for BSPs, and call for stable, long-term structures to improve investment viability. On the other hand, several studies emphasize the benefits of short-term markets. Specifically, Ramos et al. [51] suggest that while forward contracts are useful in early-stage LFMs, short-term procurement becomes more efficient as the market matures, enabling real-time matching, better price signals, and more responsive flexibility management. Similarly, Michaelis et al. [52] emphasize that an efficient low-carbon LFM should operate on a short-term timescale, with trading starting day-ahead and closing shortly before delivery. Their work suggests that short-term design enhances congestion management by allowing flexibility to be procured closer to real-time, improves market transparency and competition, and lowers entry barriers.

Market mechanisms are discussed in 35.6 % of the papers analyzed, reflecting the importance in defining how flexibility services are procured and remunerated within LFMs to ensure efficiency and fair competition among DERs. Van de Water et al. [53] explore three price formation mechanisms for local electricity markets (system-determined, auction-based, and negotiation-based) using the Multi-Criteria Mapping method to capture stakeholder preferences. Their analysis is supported by a simulation based on the BioZon pilot case study in the Netherlands. The results show that system-determined pricing is preferred in early-stage, highly concentrated markets due to its simplicity and transparency; auction-based mechanisms become more suitable as markets mature, and competition increases; while negotiation-based approaches are most effective in low-concentration, peer-to-peer environments in which individual preferences are key. On the other hand, Wang et al. [54] emphasize the importance of tailoring LFM pricing strategy to the specific characteristics of distribution networks. They propose a two-stage, market-aware framework that combines long-term planning (through optimal siting and sizing of ESSs), with short-term operation, managed via LFMs cleared using distribution locational marginal prices. These prices capture grid losses and congestion effects, offering accurate and fair price signals to DERs participating in the market. Mehinovic et al. [55] also emphasize the importance of incorporating the locational state of the distribution network into local market-clearing mechanisms. They develop a centralized LFM clearing model that explicitly integrates grid-aware sensitivity coefficients to dynamically assess the impact of flexibility asset locations on congestion and voltage regulation. Unlike static approaches, these coefficients are recalculated based on the real-time operating state of the grid, allowing the iterative market-clearing process to accurately reflect the physical network conditions.

Finally, *local energy communities* are increasingly recognized as a key topic in the development of LFMs, with 27.4 % of the reviewed studies addressing their role as a potential regulatory mechanism to foster end-user participation. Several contributions assess the financial viability of Energy Communities (ECs) across various European regulatory frameworks [56], while others specifically examine their integration into distribution grids. Taxt et al. [57] propose a scenario-based framework that explores how different DSO roles and levels of regulatory decentralization shape EC engagement in LFMs. The paper defines four integration scenarios, illustrating how ECs may range from passively responding to price signals to actively managing flexibility and interacting with DSOs through market platforms or bilateral contracts. Complementarily, García-Muñoz et al. [58] stress the importance of evaluating the flexibility potential of ECs when DSOs operate LFMs. Given privacy constraints that limit visibility into end-user behavior, the study identifies statistical patterns in EC operations as a promising approach to estimate aggregate flexibility provision, thereby enabling DSOs to plan LFMs effectively.

2.2. Service typology

The studies analyzing the flexibility services provided by DERs to DSOs are classified by the type of service addressed, as shown in Fig. 6. The defined subcategories include *active power management*, *voltage services*, *frequency services*, and *emergency services*.

Active power management emerges as the primary area of interest (49.7 % of the total occurrences). Several studies focus on demonstrating the flexibility potential and technical feasibility of DR strategies to enhance distribution network operations [59,60]. Zhang et al. [59] propose a market-clearing framework that explicitly rewards the flexibility offered by data centers through load shifting. This is achieved via virtual links, which represent non-physical pathways enabling data centers to relocate computing tasks across space and time. The results show a reduction in price volatility, improved system efficiency, and ensured cost recovery. Similarly, Berg et al. [60] assess the flexibility of residential activity-driven appliances (e.g., dishwashers, washing machines, dryers and ovens) for grid services. Using a bottom-up approach and high-resolution data from 564 households, they quantify flexibility at both building and grid scales, revealing the potential of domestic appliances to contribute to LFMs, particularly when aggregated at the regional level. Other works focus on the optimal control of end-users to enhance DR provision. Kalogeropoulos et al. [61] develop and test both centralized and distributed Model Predictive Control (MPC) strategies for managing DR in LV networks. Simulations on the IEEE European LV Test Feeder show that combining energy storage with load shifting reduces balancing energy by up to 60 % and effectively prevents congestion. The distributed MPC approach, in particular, proves well-suited for real-world applications, achieving nearly identical results to centralized control while preserving data privacy. On the other hand, *active power management* is also addressed on the generation side. Liere-Netheler et al. [62] propose a discrete optimization method to manage DG curtailment for congestion mitigation. Their approach minimizes real power adjustments and system losses while accounting for the discrete controllability levels typically used in German feed-in management (e.

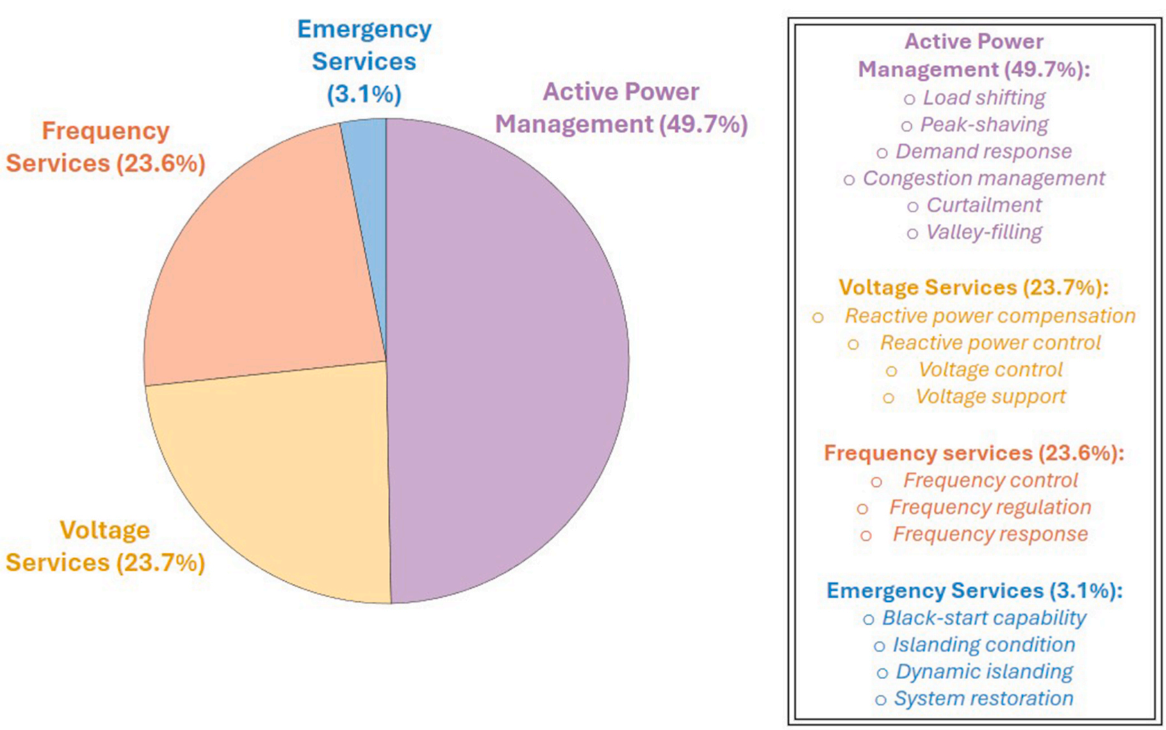

Fig. 6. Breakdown of the service typology macro-area into thematic subcategories.
The pie chart shows the relative share of publications addressing each subcategory within the service typology dimension. Keywords associated with each subcategory are listed alongside.

g., 100 %, 60 %, 30 %, 0 %). Applied to an IEEE 14-bus test system, the method resolves multi-level congestions efficiently, even under contingency scenarios. Results show that using finer curtailment increments (e.g., 10 %) significantly reduces curtailed energy and associated compensation costs. Finally, some studies highlight the potential of BESS as an effective solution for *active power management* in distribution networks. Spiliotis et al. [63], for instance, show that, by temporally shifting power flows, storage helps DSOs alleviate congestion. Using optimization models applied to a 34-node test feeder, the study demonstrates that stationary and mobile BESS can lower total system costs by 28 % and an additional 4 %, respectively, while also minimizing PV curtailment and distribution capacity expansion.

Voltage services are also a prominent topic in literature, addressed by 23.7 % of the reviewed studies. Interest in this area has grown significantly following recent updates to technical connection standards across Europe, aligned with ENTSO-E grid codes [64,65], which have formalized the role of voltage support services in distribution networks. Canizés et al. [66] develop and test a methodology to provide ancillary services in LV distribution networks by adjusting DERs active and reactive power setpoints to support voltage and relieve congested lines. Using a detailed 236-bus network over a 90-day simulation, the study shows that the proposed method achieves strong impact on congestion mitigation—up to 98.87 % load reduction on critical lines— and improves consistently the bus voltage profiles. Han et al. [67] highlight the potential of enhancing voltage stability in distribution networks by leveraging the interaction between VPPs and DSOs through LFMs. A hierarchical day-ahead coordination framework is proposed, enabling DSOs to procure flexibility from VPPs to manage voltage constraints effectively. The approach incorporates robust optimization to address uncertainties in DERs behavior and employs enhanced linearized power flow models with voltage buffers for precise constraint handling. Case studies on IEEE test systems show that this coordinated market-based approach significantly improves voltage satisfaction rates.

It is worth noting that active power regulation can also be adopted for *frequency services*, which are addressed in 23.6 % of the analyzed documents. For instance, Yumiki et al. [68] propose a system-level architecture integrating transportation and energy management systems to enable EVs to provide ancillary services to distribution grids via vehicle-to-grid (V2G) schemes. The developed multi-objective model includes both primary frequency control and voltage regulation at the distribution level. Validation is provided through numerical simulations on realistic grid models and synthetic EV data, complemented by hardware-in-the-loop testing. Similarly, Anany et al. [69] investigate the potential of EVs to deliver ancillary services such as active power support, frequency regulation, voltage control, and fault ride-through. The authors develop real-time charging optimization schemes based on particle swarm optimization, which dynamically coordinate EV charging and discharging with grid dispatch signals, accounting for user preferences such as charging priority. Results show that the proposed strategy reduces EV parking station costs by 40 % and peak net load by 11 %. Finally, Zhang et al. [70] propose a novel framework based on aggregating small-scale renewable generators and BESS for frequency regulation in low-inertia power systems. Central to their approach is a dynamic schedule and control strategy, which combines forecasting and real-time control to optimize power dispatch from distributed PV, wind units, and BESS. Through simulations on a modified power system, the authors demonstrate that the proposed method significantly improves frequency stability, enhances storage utilisation, and reduces energy curtailment compared to uncoordinated operation.

Finally, the interest in *emergency services* still appears limited (3.1 % of the total). However, some works explore how DERs can enhance distribution networks' resilience through black start and islanding capabilities. For instance, Daccò et al. [71] assess the feasibility of intentionally islanding portions of public distribution networks using diesel gensets under emergency conditions. Using RMS simulations in DigSilent PowerFactory, they confirm the technical viability of such strategies. Li et al. [72] propose a two-stage resilience framework that leverages mobile BESS to enhance both black start capability and post-disaster recovery. Their simulations demonstrate that coordinated deployment with PV, diesel generators, and EVs can sustain over 90 % of critical load. On the other hand, emergency services are also explored in the context of private networks. For example, Scrocca et al. [73] analyze reconfiguration strategies in a real MV microgrid, focusing on the economic trade-off between maximizing dynamic islanding capability and minimizing switching activity. Their results indicate that prioritizing islanding capability, even at the cost of more frequent switching, yields greater economic value.

2.3. Flexibility-providing technologies

This section examines how DER technologies have been analyzed in the literature for their role in providing ancillary services to DSOs. The occurrence of the main technologies across the reviewed studies is shown in Fig. 7. Five main technology classes can be identified: *synchronous generators*, *variable RES*, *storage systems*, *electric vehicles*, and *demand response* from flexible loads.

Synchronous generators are the most commonly addressed technology in the literature for providing flexibility to DSOs, appearing in 52.6 % of the reviewed studies, reflecting their traditional role in delivering such services. Calderaro et al. [74], for instance, investigate the impact of distributed synchronous generators on both steady-state and transient behavior in a real Italian distribution network. Their study evaluates the effects of synchronous generators integration on local voltage regulation, system stability, and protection schemes, also assessing the feasibility of islanded operation. The results highlight the dual role of synchronous generators: they can support active and reactive power delivery and enable islanding in some cases, but may also introduce instability, especially when inertia is low. However, Salim et al. [75] show that, by regulating the power-factor of distributed synchronous machines, operators can actively tune the damping of local electromechanical oscillation modes, thereby supplying important flexibility support to distribution networks and promoting stable operation even in islanded microgrid scenarios.

Variable RES comprises about 25.6 % of the analyzed studies, recognizing distributed PV and wind as active sources of grid flexibility. For example, Chalise et al. [76] propose an active power curtailment strategy for small wind turbines to mitigate overvoltage issues in residential feeders. Their approach leverages a voltage droop-based control, implemented through small adjustments to turbine blade pitch angles. Through real-time simulation of a rural feeder with 96 wind turbines, the study demonstrates that the proposed method effectively supports feeder voltage regulation while reducing network losses and power fluctuations. From a broader perspective, Karimi et al. [77] review various PV mitigation strategies, such as active power curtailment and smart inverter Volt/Var control, highlighting their effectiveness in dynamically absorbing or injecting reactive power to stabilize local voltages. Finally, Prionistis et al. [78] demonstrate that coordinated reactive power injections from converter-connected renewables within active distribution networks can significantly enhance voltage stability margins at the distribution level. Specifically, their study proposes a two-level control framework, combining central coordination with local feeder controllers.

Storage systems, represented primarily by BESS, comprise 17.9 % of the analyzed works. Prakash et al. [79] provide a comprehensive review of BESS applications in distribution networks, distinguishing between short-term ancillary services, such as voltage support, frequency regulation, and black start, and long-term services like peak shaving and congestion management. They also highlight key barriers to BESS deployment in LFMs, including economic uncertainties, battery degradation, regulatory gaps, and coordination challenges with other DERs. In a more focused contribution, Taltavull-Villalonga et al. [80] investigate the integration of BESS into optimal power flow models to address

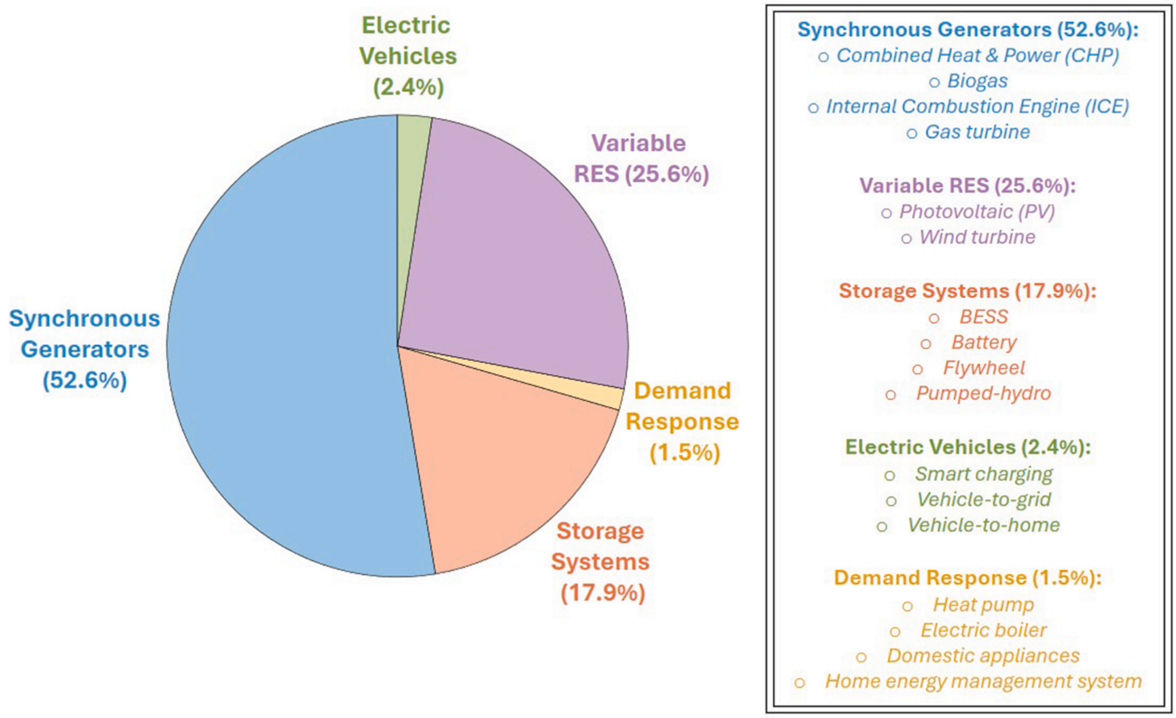

Fig. 7. Breakdown of the flexibility-providing technologies macro-area into thematic subcategories.
The pie chart shows the relative share of publications addressing each subcategory within the flexibility-providing technologies dimension. Keywords associated with each subcategory are listed alongside.

congestion and reduce losses in distribution networks. By comparing two optimal power flow formulations and applying them to a real Spanish feeder, the authors show that both approaches effectively alleviate congestion and yield similar battery dispatch patterns to maintain operational security. Moreover, optimal battery scheduling is found to enhance voltage profiles and strengthen local grid resilience.

Although *electric vehicles* appear in only about 2.4 % of the reviewed studies, they are anticipated to become a significant source of flexibility through V2G capabilities. For instance, Shafie-Khah et al. [81] develop a two-level stochastic programming framework to optimize the operation of EVs in distribution networks with high shares of renewable energy. The upper level seeks to maximize the parking lot operator's profit by optimally scheduling participation in energy and ancillary services markets, while the lower level minimizes system costs for the DSO by addressing renewable intermittency and enforcing network constraints. The study demonstrates that stochastic modeling provides more favorable outcomes compared to deterministic approaches. Similarly, Alam et al. [82] propose a dynamic V2G control strategy based on a trapezoidal charging and discharging profile that synchronizes EV battery usage with solar PV generation and local demand. In this approach, EVs are charged during midday solar peaks to alleviate overvoltage and discharged during evening demand peaks to support local loads. The strategy includes real-time adjustments to accommodate battery availability fluctuations caused by driving needs or PV variability. Simulation results show that this method outperforms constant-rate charging in mitigating voltage issues and maintaining battery readiness.

Finally, *demand response* solutions appear in about 1.5 % of the literature, focusing on the activation of flexible loads across residential, commercial, and industrial sectors. Siano [83] provides a comprehensive overview of DR potential in smart grids, highlighting its role in enhancing system reliability, reducing peak demand, and deferring costly infrastructure upgrades. The study classifies DR programs into rate-based, incentive-based, and bid-based mechanisms, and emphasizes the importance of enabling technologies, such as advanced metering infrastructure and automated control systems, for facilitating consumer participation. Fotouhi Ghazvini et al. [84] propose a market-based mechanism for managing congestion in active distribution networks, specifically addressing overloads caused by the uncoordinated operation of EVs and HPs. The authors advocate for retail electricity providers, rather than DSOs, to implement DR programs through centralized coordination of home energy management systems. Their results show that combining dynamic tariffs with power-based network charges is particularly effective in alleviating line congestion and enhancing network efficiency.

2.4. TSO-DSO coordination mechanisms

Other studies focus on TSO-DSO coordination mechanisms, which represent a key challenge for the effective implementation of LFMs. As illustrated in Fig. 8, the identified subcategories for this macro-area include *resources management*, *coordination mechanisms*, *data exchange & communication*.

The vast majority of works focus on *resources management*, covering 64 % of the identified works. Talaeizadeh et al. [85] propose a decentralized, non-iterative energy management system to coordinate DERs participation in both wholesale energy markets and LFMs through TSO-DSO integration. The model enhances joint market clearing for energy and flexibility by dynamically selecting between TSO- or DSO-markets based on network conditions and the value of unmet flexibility. Simulation results show that the approach closely matches centralized market performance while significantly reducing computational burden and increasing the volume of delivered flexibility. Similarly, Vagropoulos et al. [86] introduce a market-based TSO-DSO coordination framework aligned with the structure of European electricity markets. The key innovation lies in allowing DSOs to participate in the TSO balancing market, submitting "Priority Price-Taking" offers that represent the net effect of their local congestion management actions. This enables the TSO to account for distribution-level flexibility in system-wide balancing without requiring extensive data exchange.

Furthermore, *coordination mechanisms* are broadly explored in the

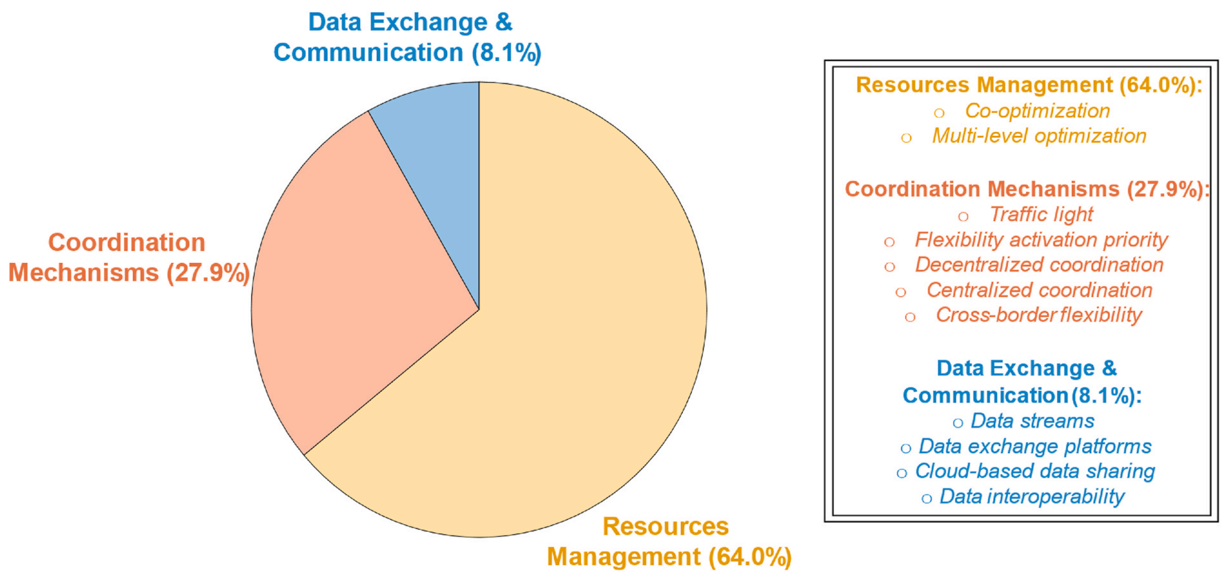

Fig. 8. Breakdown of the TSO-DSO coordination mechanisms macro-area into thematic subcategories.
The pie chart shows the relative share of publications addressing each subcategory within the TSO-DSO coordination mechanisms dimension. Keywords associated with each subcategory are listed alongside.

literature, accounting for 27.9 % of the reviewed studies, with a strong focus on the dichotomy between centralized and decentralized schemes. For instance, Nikkhah et al. [87] propose a decentralized coordination strategy between transmission and distribution networks aimed at maintaining voltage security in the integrated power system. The method relies on an iterative process in which the TSO performs a centralized optimization to minimize load curtailment while ensuring a predefined voltage stability margin, and subsequently sends set-points to DSOs. In response, DSOs activate local flexibilities—such as conservation voltage reduction, feeder reconfiguration, and, when available, DER flexibility—to meet the TSO's targets with minimal actual curtailment. The framework ensures rapid convergence and preserves data privacy by limiting information exchange to essential interface parameters. Nezhad et al. [88] develop a coordinated operational planning framework for congestion management across both transmission and distribution levels, structured around a two-stage market model encompassing day-ahead and real-time operations. The approach is evaluated under both centralized and decentralized flexibility procurement schemes. Simulation results demonstrate that the centralized TSO-DSO coordination significantly outperforms the decentralized alternative in terms of overall cost-effectiveness.

Finally, *data exchange and communication* are addressed in 8.1 % of the analyzed literature. Amjad et al. [89], critically evaluate and compare three cloud computing platforms—Cloudera, Amazon AWS, and Microsoft Azure—for enabling efficient and scalable data exchange between TSOs, DSOs, and other power system actors. The authors assess each platform's ability to handle use cases from the TDX-ASSIST project involving planning coordination, real-time supervision, and fault management. Experimental results reveal that all platforms successfully exchange XML-based data, but Cloudera outperforms the others in execution time. The study highlights cloud computing as a viable and secure solution to enhance interoperability and ICT infrastructure in modern power systems. Radi et al. [90] propose a novel business use case methodology to facilitate the provision of balancing services from DERs, addressing emerging coordination challenges driven by high RES penetration. The authors define standardized processes and interfaces for TSO-DSO-BSP collaboration, relying on cloud computing platforms for scalable and secure information exchange.

2.5. *Communication infrastructure and data management*

Studies related to communication infrastructure and data management can be organized in four subcategories, as illustrated in Fig. 9: *cybersecurity & data privacy*, *communication networks*, *technologies*, *communication protocols*.

Regarding *cybersecurity and data privacy*, addressed in 38.5 % of the papers, blockchain is often explored for its potential in enabling decentralized, secure transactions among DERs. Wu et al. [91] explore the foundational role of blockchain technology in enabling peer-to-peer (P2P) energy trading frameworks, emphasizing its potential to foster a trusted, user-centered energy society. Similarly, Huang et al. [92] present a blockchain-based solution to key limitations in P2P energy trading, particularly scalability, high transaction costs, and limited market realism. The authors implement a novel trading platform on the Polkadot blockchain, leveraging its high throughput and interoperability to maintain decentralization without sacrificing performance. A key innovation is the use of off-chain market clearing via MILP optimization, with results verified on-chain to preserve trust while enabling complex, multi-period scheduling. Blockchain ensures transaction privacy through pseudonymity and trustless validation, positioning the solution as both scalable and secure for large-scale P2P applications.

Communication networks are also a prominent topic in the literature, addressed by 38.2 % of the reviewed studies. Many contributions focus on optimizing the use of Internet of Things (IoT) technologies in power systems through advanced communication strategies. Li et al. [93] present a multi-objective optimization method for designing communication topologies in Wireless Sensor Networks (WSNs) for IoT-enabled smart buildings. Formulating the problem as an integer program solved via a genetic algorithm, they simultaneously optimizes system control performance, network energy consumption, and network stability. When applied to a multi-zone air-conditioning system, the optimized topology achieved control performance comparable to fully connected networks, while significantly reducing energy consumption and enhancing network lifetime. Dai et al. [94] propose a three-stage techno-economic framework to unlock the flexibility potential of IoT-enabled appliances, distributed PV + BESS systems, and EV smart charging within LFMs. The model coordinates smart homes, microgrid operators, and the DSO through a Stackelberg game, enabling decentralized optimization while preserving user privacy. Results show significant cost reductions for DSOs and greater smart home participation,

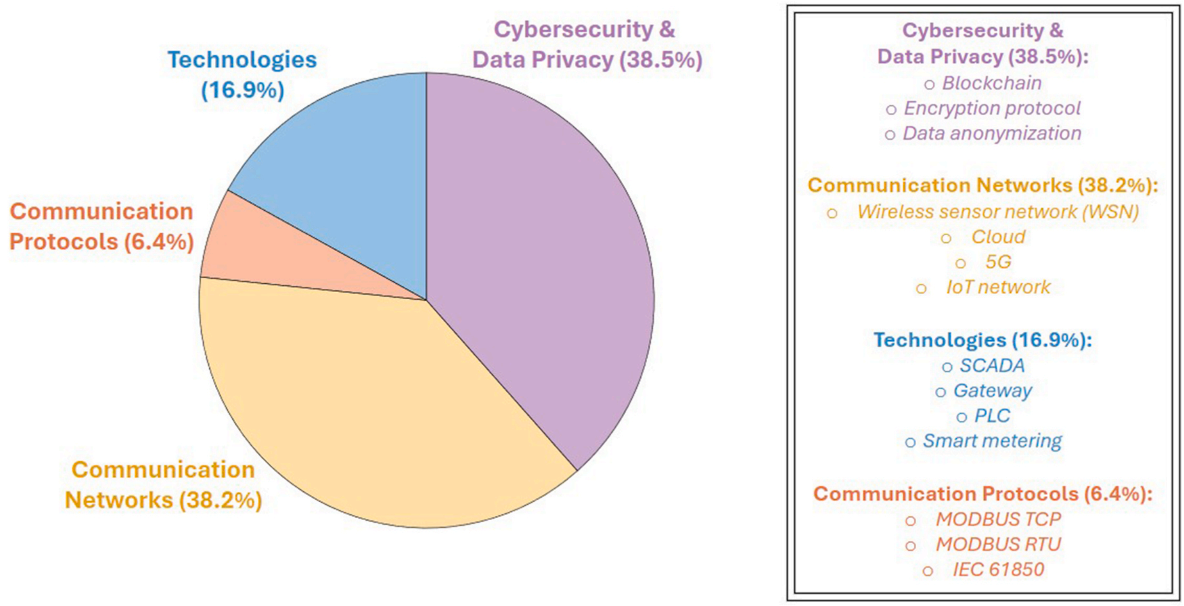

Fig. 9. Breakdown of the communication infrastructure & data management macro-area into thematic subcategories.
The pie chart shows the relative share of publications addressing each subcategory within communication infrastructure & data management dimension. Keywords associated with each subcategory are listed alongside.

contingent on the effective operation of communication channels between IoT devices, microgrid operators, and the DSO.

Technologies for communication and data management are discussed in 16.9 % of the reviewed literature. In study [95], the authors present a critical review of SCADA (supervisory control and data acquisition) and PLC (programmable logic controller) technologies, emphasizing their roles in automating and securing energy systems within smart buildings. SCADA systems are identified as key enablers for real-time monitoring, control, and data acquisition across applications such as electricity distribution, renewable energy integration, and water management, especially as they evolve toward IoT-based architectures. PLCs are recognized for their reliability and noise resistance, supporting functions like BESS management, renewable energy integration, and overall system automation. The study also features a case study of a critical building, demonstrating how a SCADA–PLC system, equipped with redundant power supplies and communication networks, can ensure high operational reliability and continuous service. Complementing this perspective, Dangwal et al. [96] focus on the security dimension of SCADA-enabled IoT systems. They propose a novel intrusion detection scheme based on the DNP3 communication protocol, which, despite its widespread use in critical energy infrastructure, lacks native security features. Their machine learning–based approach effectively detects and classifies eight types of cyberattacks using data from real-world testbed scenarios.

Finally, the implementation of secure and efficient *communication protocols* is crucial for the operation of LFMs, a topic explored in 6.4 % of the reviewed studies. In study [97], the authors evaluate the scalability of the Modbus TCP communication protocol for monitoring and controlling DERs in an energy district. Focusing on a self-consumption system integrating PV generation and BESS, they use OMNeT++ simulations to assess Modbus TCP performance under different network conditions. The analysis measures the "polling time" between a central Modbus client and multiple DERs in a star topology. Results indicate that under low bit error ratios, Modbus TCP can reliably scale to over 140 servers while meeting the operational requirement of completing a full polling cycle within 1 min. Schmutzler et al. [98] propose an extension of the IEC 61850 standard to address the current lack of standardized communication models for EV-grid integration. Leveraging the vehicle-to-grid communication interface defined in ISO/IEC 15118, the authors introduce three new logical nodes representing EV supply equipment, outlets, and connected EVs. A proof-of-concept implementation confirms the technical feasibility of the proposed model, highlighting its potential to enable automated EV charge control and support the broader market adoption of EVs as flexibility-providing assets.

3. Overview of local flexibility markets in Europe

The implementation of LFMs across Europe exhibits considerable heterogeneity, shaped by differences in national regulatory frameworks, energy market architectures, and operational practices. First of all, it is essential to outline the general structure of LFMs, highlighting the main stakeholders and their respective roles. Fig. 10 schematically illustrates the process of flexibility procurement by DSOs. An independent third-party entity operates a market platform that enables the interactions between DSOs and BSPs. DSOs issue flexibility requests, and BSPs can submit flexibility bids if their DERs comply with the technical requirements. Once a BSP secures a contract for a specific service, it is responsible for transmitting the activation signal sent by the DSO to its DERs. The market structure, remuneration mechanisms, and technical requirements vary across LFMs and will be explored in greater detail later in this section.

National contexts examined in this study are summarized in Table 2. They have been selected based on the availability of data on existing LFMs, as well as their ability to offer a balanced representation of different stages of market development, including mature markets (e.g., in Great Britain and the Netherlands) alongside more recent initiatives (e.g., in Italy and Portugal).

It should be noted that other LFMs are also active in Europe, such as Effekthandel Väst in Sweden [99], FinFlex in Finland [100], and Euroflex in Norway [101]. In addition, new designs are under development within dedicated demonstration projects. An example is found in Spain, where the market operator OMIE and the national energy agency IDAE are jointly designing a Spanish LFM system under the IREMEL project [102].

However, the set of case studies analyzed here is considered sufficient to illustrate the diversity of possible design approaches to local flexibility procurement. For instance, GB shows a mature forward

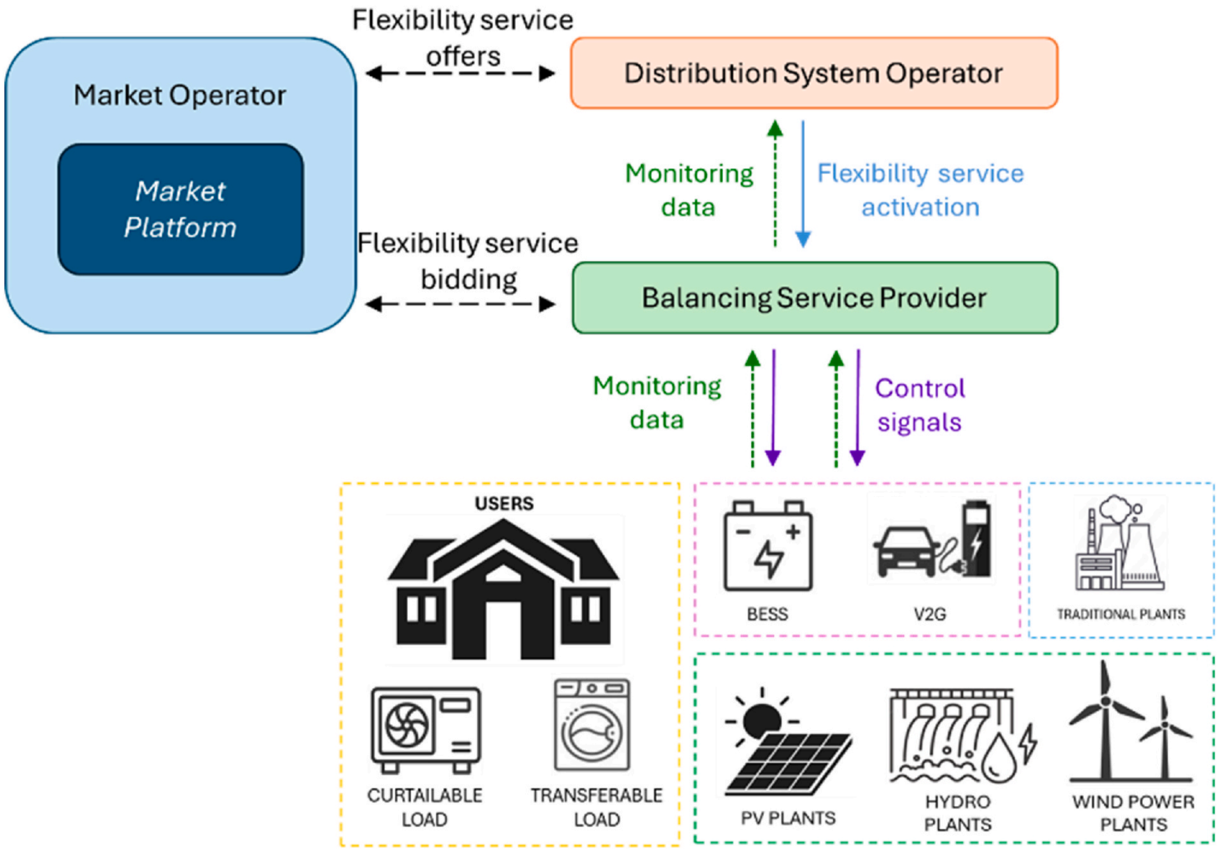

Fig. 10. Schematic representation of a generic LFM structure.
The DSO creates auctions on a market platform managed by a third-party entity. BSPs can participate by submitting bids. If a BSP is awarded a contract, it may be required to activate the service either during predefined time windows or upon request via a dispatch signal from the DSO. In all cases, the BSP is responsible for ensuring the activation of the DERs under its control whenever the contracted service is needed.

Table 2
Overview of European countries included in the analysis and the corresponding DSOs involved in LFMs.

Country	Involved DSOs	Project Name	Market Platform	Procured Services	Starting Year
Great Britain	Electricity North West (ENW) [103]	–	Electron Connect [104] & Piclo Flex [105]	**Active Power** (PR, SU, OU, VA + OU)	2018
	National Grid Electricity Distribution (NGED) [106]	–	Market Gateway [107] & Piclo Flex	**Active Power** (SU, OU, SA + OU)	2018
	Northern Powergrid (NPg) [108]	–	Piclo Flex	**Active Power** (SU)	2018
	SP Energy Networks (SPEN) [109]	–	Piclo Flex	**Active Power** (SU, OU, SA + OU, VA + OU) **& Reactive Power**	2018
	Scottish and Southern Electricity Networks (SSEN) [110]	–	Electron Connect	**Active Power** (SU, OU, SA + OU, VA + OU)	2018
	Uk Power Networks (UKPN) [111]	–	Local Flex [112]	**Active Power** (SU, SA + OU)	2018
Netherlands	Liander [113], Enexis [114], Stedin [115], Rendo [116], Coteq Netbeheer [117], Westland Infra [118]	GOPACS	GOPACS interacting with trading platforms such as ETPA [119] and EPEX-SPOT [120]	**Active Power** (Redispatch and Capacity Restriction)	2018
France	Enedis [121]	–	Flexibilitè Enedis [122]	**Active Power**	2020
Sweden	Ellevio [123], Vattenfal Eldistribution [124]	Sthlmflex	NODES [125]	**Active Power**	2020
Portugal	E-REDES [126]	FIRMe	Piclo Flex	**Active Power**	2023
Slovenia	Elektro Ljubljana [127]	–	Moj Elektro	**Active Power**	2023
Italy	E-distribuzione [128]	EDGE	Piclo Flex	**Active Power**	2023
	Areti [129]	RomeFlex	GME	**Active Power**	2023
	Unareti [130]	MiNDFlex	GME	**Active Power** (Standard and Emergency)	2024

market framework, offering a wide portfolio of standardized flexibility products. France and Portugal also rely on forward markets, where selected units are contracted through multi-year bilateral agreements with their respective DSOs. Italy and Sweden are experimenting with hybrid models that combine forward contracting with spot-based activation mechanisms. The Netherlands, through GOPACS, illustrates a shared TSO–DSO platform for congestion management, directly integrated with wholesale market schedules. Slovenia, by contrast, focuses on LV networks and direct interaction with end consumers, offering a different perspective on how LFMs can be implemented at a smaller scale.

The remainder of this section discusses in detail the most important characteristics of these selected initiatives.

Since 2018, in Great Britain (GB), all six DSOs have been procuring local flexibility services through five standardized active power regulation services: Peak Reduction (PR), Scheduled Utilisation (SU), Operational Utilisation (OU), Scheduled Availability & Operational Utilisation (SA + OU), and Variable Availability & Operational Utilisation (VA + OU) [131]. These ancillary services, as well as other general market aspects, are commonly defined by the ENA [132], a not-for-profit industry body representing energy network operators in the United Kingdom and Ireland. Conversely, other elements remain at the discretion of individual DSOs, allowing them to tailor specific parameters and regulatory characteristics to their distribution network needs. For example, the six DSOs operate through different market platforms. Among these, the most widely adopted platform is PicloFlex, a third-party solution specifically designed for local flexibility procurement. Other DSOs adopt ElectronConnect, while NGED has developed its own proprietary platform, Market Gateway. Meanwhile, UKPN has opted for Local Flex, operated by EPEX Spot. Moreover, despite a common framework, each DSO independently decides which flexibility service to procure. For instance, SPEN is currently the only DSO that has launched auctions for procuring reactive power regulation services; however, these auctions are currently limited to capacity reservations for future operational years, with no recorded activations to date.

In the Netherlands, *GOPACS* [28] has been in operation since 2018, enabling both the TSO and participating DSOs to issue open calls for active power regulation services to mitigate network congestion. These calls are published on a dedicated congestion management portal but are also integrated with external trading platforms, such as EPEX Spot and ETPA, enabling BSPs to participate and submit offers directly through those platforms to provide the requested services.

In France, the DSO Enedis manages nearly the entire national distribution grid, except for island networks. To procure local flexibility services, Enedis divides the national distribution network into zones, assessing congestion issues and determining the most effective solutions. Based on these assessments, auctions are launched in zones where flexibility services are required, with technical specifications tailored to address the identified network constraints. Since 2020, Enedis has published these auctions on its own platform, where BSPs that meet the technical requirements can register, participate, and submit offers.

In Sweden, the *Sthlmflex* pilot project [31], launched in 2020, led to the development of the country's first LFM. The project aimed to assess whether upward active power regulation services could effectively alleviate persistent congestion issues in the Stockholm region during winter. Several key stakeholders participated in the initiative: Svenska kraftnät (Sweden's TSO) [133] served as the project lead; Ellevio, the DSO for the city of Stockholm, acted as a flexibility buyer together with Vattenfall Eldistribution; E.ON Energy Distribution [134] provided network operation forecasting tools; NODES operated the market platform through which DSOs procured flexibility services. The project has officially concluded due to the very low market liquidity observed during the pilot phase. Indeed, Ellevio has stated that, in the short term, LFMs are not a suitable solution for congestion management in Stockholm, and is therefore exploring alternative approaches through other projects [135].

In Portugal, the DSO E-Redes launched the *FIRMe* pilot project to procure local flexibility services, leading to the first auctions in July 2023 for eight districts across the country, focusing exclusively on upward active power regulation. In March 2024, following technical assessments of the winning units, the first two-year bilateral contracts were signed between the DSO and BSPs managing the selected units.

In Slovenia, Elektro Ljubljana, the DSO operating the country's largest distribution network, launched a pilot project in 2023 aimed at procuring DR services from LV consumers to address transformer overloading issues observed during winter [136]. The first open calls for flexibility procurement were issued in September 2023, and consumers located in the targeted areas were directly contacted. Interested participants registered on the Moj Elektro platform [137], through which they were able to submit bids indicating both the price and quantity of flexibility they were willing to provide. This setup removed the need for end-users to interface with a BSP, granting direct market access to citizens. To further encourage participation, a € 50 incentive was offered to each consumer who registered and took part in the auctions, regardless of whether they ultimately delivered the service.

In 2023, Italy launched its first pilot projects for the development of LFMs, led by the country's three largest DSOs [138]: E-Distribuzione, Areti and Unareti. In line with the National Regulatory Authority (ARERA) Resolution 352/2021 [32], each DSO was allowed to independently design its own market architecture. E-Distribuzione initiated the first phase of its pilot project, *EDGE* [33], across four provinces, identifying specific flexibility perimeters within each area where active power regulation services were required to mitigate grid congestion. The corresponding auctions were launched starting from November 2023 via the PicloFlex [105] platform. At the same time, Areti introduced *RomeFlex* [34], an LFM designed for the city of Rome, based on a hybrid market structure combining both forward and spot mechanisms. The market platform used in the project was managed by Gestore dei Mercati Energetici (GME), the national wholesale energy market operator [139]. In 2024, Unareti launched *MiNDFlex* [35], aimed at procuring local flexibility services in Milan. In its first stage, the initiative focused on a critical area of the city supplied by a single primary substation. Although the market architecture and platform were the same as those adopted in *RomeFlex*, Unareti introduced different technical specifications for the contracted services, distinguishing between two product types: standard and emergency services.

This overview of LFMs development across Europe highlights a considerable diversity in how local markets are being designed, with different services procured and multiple market platforms often coexisting within the same country. Despite this regulatory flexibility, all initiatives adhere to the core principles of the European Directive 2019/944 [42], including technological neutrality and facilitation of resource aggregation to fully leverage the potential of DERs. Notably, to date, all existing LFMs have focused on active power regulation services, although plans to expand into reactive power procurement are emerging, as demonstrated by the GB case.

The remainder of the section offers a comparative and structured overview of the different projects analyzed, focusing on three main aspects: *market products and remuneration mechanisms*, *baseline definition methodologies*, and *market outcomes*. It is important to note that the snapshot of European LFMs presented in the following subsections reflects the regulatory and market conditions as of early 2025. Consequently, any developments occurring after this date—such as updates to Italy's regulatory framework following the first year of pilot projects—are not considered. Given the fast-paced evolution of LFMs across Europe, providing a snapshot that remains fully up to date is inherently challenging, as regulatory frameworks and market practices continue to evolve. Nevertheless, the comparative value of this analysis remains valid over time, as it offers a structured basis for evaluating different approaches to procuring flexibility from DERs.

3.1. Market products design and remuneration schemes

For each LFM, DSOs defined one or more market products to address their specific grid management needs. These products are characterized by minimum technical requirements and a remuneration scheme that varies according to the product's intended objectives. Specifically, four aspects of product design were analyzed.

- Techno-economic requirements. We considered:
  - the minimum bid size that can be offered, which influences whether small DERs and aggregators can participate;
  - the maximum activation lead time, reflecting how quickly BSPs must adjust active power;

Table 3
Local flexibility services and related techno-economic features by country.

Country	Service Name	Min Quantity	Availability Period	Availability Auction	Utilisation Period	Activation Timing	Service Direction	Max Activation Time	Min Duration Time	Payment Structure	Pricing Method
Great Britain	Peak Reduction (PR)	10 kW	–	–	Settlement periods	At trade	Upward(by demand turn down)	–	30min	Utilisation only	Pay As Bid
	Scheduled Utilisation (SU)	0/10 kW [a]	–	–	Settlement periods/EFA blocks [b]	At trade	Both	–	30min	Utilisation only	Pay As Bid/Pay As clear [a]
	Operational Utilisation (OU)	0/10 kW [a]	–	–	Minutes	Real time/Real time/Week-Ahead [b]	Both	2min/ 15min/-[b]	30min	Utilisation only	Pay As Bid/Pay As clear [a]
	Scheduled Availability & Operational Utilisation (SA + OU)	0/10 kW [a]	Settlement Periods	Months-Ahead	Minutes	Real time/Day-Ahead [b]	Both	2min/- [b]	30min	Utilisation + Availability	Pay As Bid/Pay As clear [a]
	Variable Availability & Operational Utilisation (VA + OU)	0/10 kW [a]	Settlement Periods	Months-Ahead	Minutes	Real time/Real time/Day-Ahead/ Week-Ahead [b]	Both	2min/ 15min/-/- [b]	30min	Utilisation + Availability	Pay As Bid
Netherlands	Redispatch	100 kW	–	–	One or more ISPs	At trade (Intraday)	Both	–	15min	Utilisation	Pay As Bid
	Capacity Restriction	–	Settlement Periods	Day-Ahead	One or more ISPs/Settlement Periods [b]	Real time/At trade (Day-Ahead) [b]	Upward(by demand turn down)	–	–	Availability	–
France	–	500 kW	Settlement Periods	Months-Ahead	One or more ISPs	Real time	Both	15min +10min	30min	Utilisation	Pay As Bid
Sweden	ShortFlex	100 kW	–	–	One or more hours	At trade(Day-Ahead or Intraday)	Upward	–	60min	Utilisation	Pay As Bid
	ShortFlex Availability	100 kW	Settlement Periods	Days-Ahead	One or more hours	Real time	Upward	–	60min	Utilisation + Availability	Pay As Bid
	LongFlex	100 kW	Settlement Periods	Months-Ahead	One or more hours	Real time	Upward	–	60min	Utilisation + Availability	Pay As Bid
Portugal	Restore/Dynamic/ Secure	10 kW	Settlement Periods	Months-Ahead	One or more ISPs	Real time	Upward	15min	Auction Specific	Utilisation + Availability/ Utilisation/ Availability	Pay As Bid
Slovenia	–	1 kW	Settlement Periods	Months-Ahead	One or more ISPs	Real time	Upward	15min	–	Utilisation	Pay As Bid
Italy	–	25 kW/3 kW [a]	Settlement Periods	Months-Ahead	One or more ISPs	Real time/At trade (Day-Ahead or Intraday) [a]	Both	60min/ 15min [a]	15min	Utilisation + Availability	Pay As Bid

[a] Specification dependent on the DSO.
[b] Specification dependent on the type of product contracted with the DSO.

- the direction of service provision (upward, downward, or bidirectional).
- Availability auction characteristics. To understand how LFMs secure flexibility capacity in advance, we examined:
  - the contracting period for availability (e.g., daily, weekly, seasonal), which affects BSPs' ability to plan resources;
  - the timing of availability auctions, as this determines when BSPs must commit capacity relative to wholesale and balancing markets.
- Utilisation characteristics. We considered:
  - whether activation is defined over a pre-determined time window or dispatched on a minute-by-minute basis;
  - the dispatching times, i.e., when DSOs issue activation requests.
- Remuneration schemes. Finally, to capture the economic incentives for participation, we analyzed:
  - whether BSPs are remunerated for availability only, for utilisation only, or through a two-part scheme covering both;
  - the pricing mechanism adopted in product auctions.

Table 3 presents the flexibility products designs identified in the analyzed LFMs, organized by country. For some countries, such as GB and Italy, products have been grouped under a single section, despite potential differences could exist among those procured by different DSOs. Moreover, variations may also occur at the individual DSO level, with the same product potentially offered with differing activation lead time and/or maximum duration.

In GB most services have a minimum threshold of offered flexibility, *Min Quantity,* equal to 10 kW, although some DSOs have already removed this limit, and the general trend is to eliminate it entirely. A common requirement across all services is a minimum guaranteed duration of service provision, *Min Duration Time,* of 30 min. Auctions follow a pay-as-bid pricing method, although NGED may adopt a pay-as-clear approach for certain products. Despite these common elements, the five flexibility products defined by the ENA differ in several key aspects.

1. *Peak Reduction (PR)*: Designed to reduce peak demand, this product targets consumers providing upward flexibility during predefined settlement periods. Auctions are held well in advance (e.g., season-ahead), setting quantity and utilisation price. No dispatch signal is sent from the DSO, as delivery is requested during predefined periods. Remuneration is based solely on actual utilisation (£/MWh).
2. *Scheduled Utilisation (SU)*: Intended to manage seasonal peaks and defer reinforcement, SU is open to both consumption and generation units offering upward or downward flexibility during predefined time blocks (Electricity Forward Agreement-EFA blocks, standardized trading periods used across electricity markets, or specific settlement periods). Like PR, auctions define quantity and utilisation price well in advance, delivery is requested without a DSO's dispatch signal, and payment is based on utilisation only.
3. *Operational Utilisation (OU)*: Typically used to restore network supplies following unplanned outages or faults, particularly in cases where regulatory frameworks do not permit availability payments (e.g., customer interruptions). OU is open to both consumption and generation units that can adjust their electricity exchange in response to DSOs' real-time needs. Based on the timing when the BSP is instructed to activate their units (*Activation Timing*) and the consequent maximum time allowed between the reception of the activation signal and the activation of the entire contracted capacity (*Max Activation Time*), DSOs distinguish three sub-products:
   a. Real-time dispatch with *Max Activation Time* of 2 min,
   b. Real-time dispatch with *Max Activation Time* of 15 min,
   c. Dispatch instruction issued a week in advance, with the service required to be activated at the start of the specified time window.

   BSPs are paid for utilisation only (£/MWh) for each sub-product.
4. *Scheduled Availability + Operational Utilisation (SA + OU)*: Typically used when a DSO plans flexible service contracts based on short- to medium-term forecasts of network constraints. SA + OU allows DSOs to reserve capacity for specific settlement periods and activate units in real time. Auctions are held months ahead, setting availability and utilisation prices. Two sub-products exist:
   a. Real-time dispatch with *Max Activation Time* of 2 min,
   b. Day-Ahead scheduled activation.

   BSPs are paid for both availability (£/MW/h) and utilisation (£/MWh).
5. *Variable Availability + Operational Utilisation (VA + OU)*: Typically used when a DSO plans flexible service contracts based on long-term forecasts of network constraints. VA + OU enables DSOs to reserve flexibility capacity for specific settlement periods through auctions held months in advance, while still allowing adjustments to the reserved capacity closer to real-time. Dispatch signals are then sent by the DSO based on actual real-time system needs. Four sub-products are defined depending on dispatch timings:
   a. Real-time dispatch with *Max Activation Time* of 2 min,
   b. Real-time dispatch with *Max Activation Time* of 15 min,
   c. Week-Ahead scheduled activation,
   d. Day-Ahead scheduled activation.

   BSPs are paid for both availability (£/MW/h) and utilisation (£/MWh).

In GB, for all flexibility products, dispatch notifications from the DSO to the BSP can be delivered via automated instructions, platform alerts, or phone calls. Once notified, the BSP is free to determine which of its qualified assets to activate, as long as they are located within the relevant grid area for the service. The BSP is then responsible for confirming the activation and providing real-time monitoring data to the DSO. Although each DSO currently adopts its own method for dispatch communication, there is broad consensus among stakeholders that this process should be standardized and scaled through the use of Application Programming Interfaces (APIs). APIs would enable automated, reliable, and efficient handling of dispatch signals. In support of this transition, the ENA is actively developing a standardized dispatch API.

In the Netherlands, the GOPACS platform was developed to solve congestions on both transmission and distribution networks through the activation of flexibility services. Two products are defined.

1. *Redispatch*: This product addresses real-time congestion by adjusting the power exchange of units with the grid and therefore does not require a predefined availability window. It is contracted on an intraday basis, based on requests submitted by DSOs via the GOPACS platform close to real time, and on corresponding offers from BSPs able to respond. Winning participants must guarantee a *Min Duration Time* of 15 min and are remunerated for actual activation under a pay-as-bid pricing scheme. In addition to this free bidding mode, a mandatory bidding option is also available through bilateral contracts between DSOs and BSPs. Under such agreements, the BSP commits to submitting offers for every DSO auction on GOPACS in exchange for predefined remuneration.
2. *Capacity Restriction*: This product targets consumers capable of shifting electricity usage to periods of lower network congestion. It is contracted on a day-ahead basis and remunerated in €/MW of agreed capacity reduction. Two contractual options are available:
   a. *Capacity Restriction on Demand*, where activation is dispatched by the DSO in real time;
   b. *Capacity Restriction with Time Block*, where the service window is predefined during the day-ahead auction.

In France, Enedis procures local flexibility through auctions held for specific critical areas identified by the DSO. In each auction, the DSO specifies the service direction (upward or downward), a *Min Quantity* (500 kW), the availability window, *Max Activation Time* (25 min), and a *Min Duration Time* (30 min). Participating BSPs submit bids indicating the volume offered and a utilisation price in €/MWh. If awarded, the BSP signs a three-year bilateral contract with Enedis, committing to provide the service when requested in exchange for the bid price. Importantly, the BSP may reject any individual dispatch order without penalty, provided the refusal occurs no more than 15 min after the dispatch order.

The Sthlmflex project led to the definition of three flexibility products with a structure and objectives similar to the framework observed in the GB. All products involve active power regulation in the upward direction, with an hourly time resolution. The key differences between them are as follows.

1. *ShortFlex* refers to local flexibility services contracted through day-ahead or intraday auctions for specific time intervals, with payment only for actual utilisation.
2. *ShortFlex Availability* involves reserving capacity a few days in advance, with payment both for availability and activation.
3. *LongFlex* was introduced for structural issues on the distribution network, allowing capacity reservation months in advance for multi-month periods.

As part of the project, BSPs active in the LFM were also given the opportunity to submit bids for the national mFRR service provided to the TSO Svenska kraftnät, aiming to test the coordination mechanisms between DSO and TSO. For this service, as well as all other flexibility services, activation from either the DSO or the TSO to the BSP can occur via email, API, or SMS, depending on the BSP's chosen preference during registration on the NODES platform. The BSP retains full discretion over how to allocate the dispatch signal among its qualified units.

In Portugal, E-REDES adopted a design similar to the LFM managed by Enedis in France. It relies on forward auctions to reserve flexibility capacity through two-year bilateral contracts between BSP and DSO. Three main products are procured within this framework.

1. *Restore*, which is a post-failure service aimed at supporting the restoration of the network following outages. Its remuneration scheme includes an annual availability payment and an additional payment for actual activation.
2. *Dynamic*, which is intended to ensure the operability of the network during planned maintenance activities. Availability is remunerated on an hourly basis, depending on the contracted availability window, with an additional payment provided for activation.
3. *Secure*, which is designed to support the network under normal operating conditions by managing congestion at critical points of the grid. This service is remunerated for both availability and activation.

Currently in Portugal, for all the presented products, dispatch orders are sent from the DSO to the BSP via phone call and email. It is then up to the BSP to decide how to transmit the dispatch order to its qualified resources.

The LFM developed in Slovenia targets LV users. Flexibility services are procured at the beginning of winter through auctions, followed by contracts between winning users and the DSO. These services are activated when needed to prevent overloading of previously identified critical LV/MV transformers. Remuneration is provided solely for activated services, with activation requests communicated by the DSO to the flexibility providers via SMS and email. Given the target user group, the minimum bid size is significantly lower than in other European LFMs, reaching 1 kW.

In Italy, the LFMs developed by the three participating DSOs exhibit significant heterogeneity, although all of them adopt a pay-as-bid pricing mechanism and provide remuneration for both availability and activation. E-distribuzione has implemented a market scheme similar to the Portuguese model, with forward auctions issued for specific areas of the distribution grid. Contracts between BSPs and the DSO are valid for a single season. Each auction is associated with.

1. A specified flexibility requirement (quantity and direction, i.e., upward or downward),
2. A timeslot indicating when flexibility must be reserved,
3. A maximum availability price, calculated based on the avoided grid development costs (i.e., the cost the DSO would incur under a fit-and-forget approach).

Additionally, all EDGE auctions share a set of common parameters: the maximum utilisation price is set at €500/MWh, the minimum offered quantity (*Min Quantity*) must be at least 25 kW, *Min Duration Time* is 15 min, and the *Max Activation Time* is 60 min. For BSPs managing DERs awarded in forward auctions, service activation by the DSO is communicated via Telegram, either in JSON format or as a human-readable message. In contrast, Areti and Unareti have adopted a hybrid structure, combining forward markets for capacity reservation with day-ahead and intraday spot markets for activation. This structure is more similar to the flexibility framework proposed in Sweden. The forward market is conducted months ahead of the delivery period, and each session defines a specific time window during which reserved capacity must be made available. The general requirements for participating in the forward markets of RomeFlex and MiNDFlex include a maximum availability price of 30′000€/MW/year and a maximum utilisation price of 500€/MWh, a minimum bid size of 3 kW for RomeFlex and 20 kW for MiNDFlex, a minimum service duration of 15 min for both schemes, and a *Max Activation Time* of 15 min for RomeFlex, while in MiNDFlex it varies depending on whether the contracted service is classified as *standard* (60 min) or *emergency* (15 min). Following the forward auctions, day-ahead and intraday spot markets are held to select the most cost-effective resources for activation. Participation in these spot markets is open to all BSPs, regardless of whether they reserved capacity in the forward phase, ensuring that activation is based solely on economic efficiency. Dispatch orders for units awarded in spot markets are sent by the DSO directly to the units through dedicated devices known as PGUI (Power Grid User Interface), which are mandatory for all assets qualified to participate in the LFM. However, Unareti is pointing out this requirement as an unnecessary entry barrier and is therefore moving toward a simplified architecture based on direct communication between the DSO and the BSP (e.g., via email) in future developments.

3.2. Baseline definition methodologies

In LFMs, a key challenge is accurately verifying the flexibility delivered by BSPs following a DSO activation request. This is essential both to ensure fair compensation for service utilisation and to provide DSOs a way to assess the reliability of participating BSPs. To address this issue, a baseline is usually established, representing the expected withdrawal or injection profile if no flexibility is activated. The methodology to define this baseline entails certain assumptions and should be ideally tailored to each unit in order to minimize the estimation error. While ex-post (or real-time) assessment of the baseline may be more accurate, knowing the reference baseline in advance is highly relevant for flexible units, as they may adjust their real-time operations to accurately respect the dispatching order. Baseline definition methodologies adopted in analyzed LFMs are summarized in Table 4. It is worth noting that in the Netherlands, where the GOPACS platform is jointly operated by DSOs and the TSO, no baseline is required for validating delivered flexibility. This is because each accepted bid corresponds to a modification of a market operator's commercial schedule. As a result, validation is carried out by simply comparing the updated commercial program with the actual delivery.

In most cases, DSOs offer BSPs a choice among several baseline

Table 4
Baseline methodologies used in the analyzed LFMs.

Baseline type	Computation Methodology	Parameters Set by the DSO	Involved DSOs
Historical: Average	Average power flow measured over the same time window in the past X days (without service activation), grouped by day type	-Number of days (X) to average -Day type classification	ENEDIS, Swedish DSOs, Areti, Unareti
	Same as above, but corrected with a factor based on the power flow measured H hours before service activation	-Number of days (X) to average -Day type classification -Adjustment time window (H hours)	E-distribuzione
Historical: Median	Median power flow measured over same time window in the past X days (without service activation), grouped by day type	-Number of days (X) to average -Day type classification	ENEDIS
Historical: Mean X-in-Y	Average power flow measured over the same time window in the past X days, selected from the last Y days by excluding the (Y–X) days with the highest and lowest power flows, considering only days of the same type	-Number of days (X) to average -Number of days (Y) considered for selection -Day type classification	All British DSOs
	Same as above, with correction based on power flow H hours before activation	-Number of days (X) to average -Number of days (Y) considered for selection -Day type classification -Adjustment time window (H hours)	All British DSOs, EREDES
Historical: K-Nearest Neighbors	Average power flow measured over the same time window in the past X days (without service activation), selected as the KNN-closest days to the current profile among the last Y days	-Number of days (X) to average -Number of days (Y) considered for selection	ENEDIS (consumption units only)
Recent data: Average	Average power flow measured over the last H hours	-Number of hours (H) to average	ENEDIS, E-distribuzione, Elektro Ljubljana
Recent data: Trapezoidal method	Linear interpolation between measured average consumption (over H hours) before and after service activation	-Number of hours (H) to average	ENEDIS (consumption units only)
Benchmark method	Measured average profile of similar N units not providing the flexibility service (reference group)	-Number of reference units (N)	ENEDIS (consumption units, wind & solar)
Zero	Baseline assumed as zero power flow	–	All British DSOs
User-nominated[a]	Baseline predicted using forecasting tools	–	All British DSOs, ENEDIS, Sweden DSOs

[a] Subject to DSO approval following validation tests.

calculation methods. However, the selected approach must be mutually agreed upon and specified in the contract. Most methodologies adopted by European DSOs rely on historical data from similar types of days (e.g., working days or holidays). Some methods use the average over the past X days, others use the median, with the option, applied in countries like the UK and Portugal, to exclude days with extreme (maximum and minimum) profiles. A key limitation of historical methods arises when weather conditions change significantly from one observation period (e.g., day) to the next, causing actual power exchange (in the absence of flexibility activation) to differ substantially from the historical average or median. To address this, some approaches apply a correction factor to the baseline, based on the actual unit power profile in the H hours before activation. For example, E-distribuzione uses the average of the last 15 days of the same day type (working day or holiday) and adjusts it with an additive factor, derived from the average difference between the assumed baseline and the observed power flow during the 2 h prior to service activation. An alternative approach exploits the measured power exchange immediately before activation. This approach is particularly well-suited for consumption units, and it is adopted, for example, by Elektro Ljubljana, which sources flexibility services directly from LV end-users. A more advanced method proposed by Enedis is the *benchmark* method, which calculates the baseline as the weighted average profile of a reference group of similar units non-participating in the flexibility market. When applied to wind and solar, the reference units must also be located within a certain geographical proximity to the participating unit. Additionally, some DSOs adopt a zero-baseline approach, meaning that the reference profile assumes no power exchange with the grid, and any deviation from this zero exchange is considered as offered flexibility. Finally, some DSOs allow BSPs to define their own baseline, for example using forecasting models, provided that the methodology is tested and approved by the DSO in advance.

Beyond the practices observed in the analyzed LFMs, two recent studies offer deeper guidance on baseline design and its limits. Lind et al. [140] propose a decision framework that evaluates methods by accuracy, simplicity, and integrity (resistance to manipulation). They show that no single approach suits all DER technologies and provide criteria to select methods based on resource characteristics. Ziras et al. [141] take a more critical view: baseline-based services are often ill-suited to LFMs—especially under continuous aggregator control and parallel market participation. They advocate capacity-limitation services as a simpler, more transparent alternative for managing congestions in distribution networks.

3.3. Market outcomes

Focusing on those projects with availability of historical data, it is possible an insight into the maturity level of LFMs, as well as on the potential economic opportunities for BSPs.

Fig. 11 presents the volumes auctioned in the LFMs analyzed across GB, the Netherlands, France, Portugal, Slovenia, and Italy; volumes are expressed as the total reserved flexible capacity during recent trading periods. For GB, data refers to the 2023–2024 reporting year. For the Netherlands, volumes are from 2024. For Enedis, they correspond to the capacity procured in the first auctions of 2024, which concluded in early June. In Portugal, the data reflects the contracted capacities following the first project auctions held in September 2023. In Slovenia, data refers

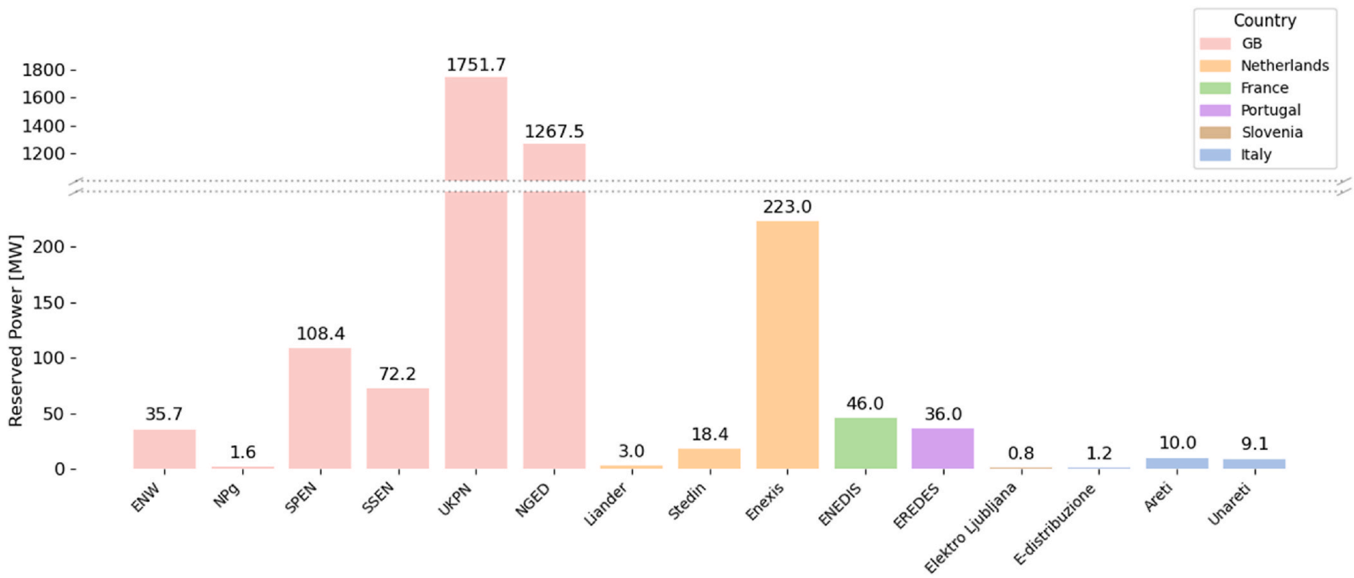

Fig. 11. Contracted capacity in the analyzed LFMs.
Vertical bars represent the total reserved power in recent auction periods for each LFM operated by the indicated DSOs. Swedish LFMs are excluded from the diagram due to data unavailability. The significantly higher contracted capacities in British and Dutch LFMs suggest a greater level of market maturity compared to other countries.

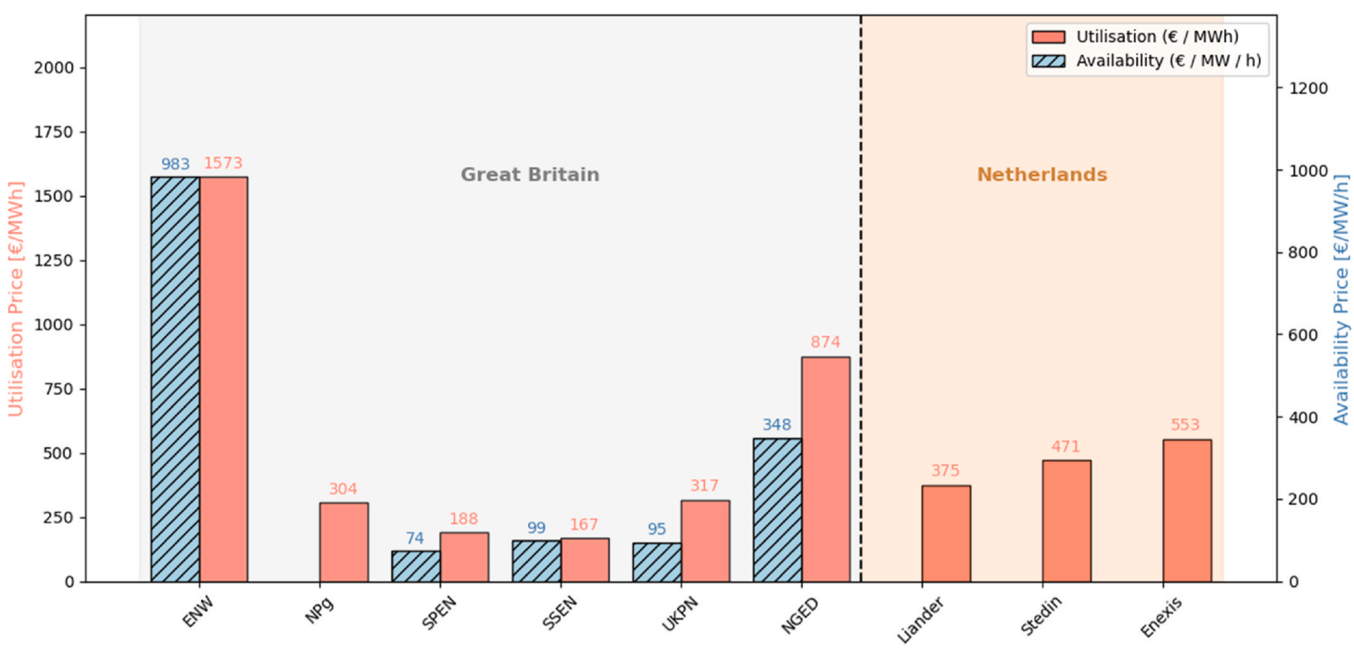

Fig. 12. Contracted average availability and utilisation prices in the British and Dutch LFMs.
The vertical bars represent the average availability and utilisation prices contracted by each DSO in the British LFMs during the 2023–2024 auction period. For the Dutch LFMs, the bars show the average prices awarded to contracted BSPs on the GOPACS platform for each DSO during 2024. Other LFMs are excluded due to significantly lower liquidity.

to the currently registered available flexibility capacity. For Italy, volumes from E-distribuzione cover the first half of the first year, including the winter and spring 2024 auctions, while for Areti and Unareti, the figures refer to the capacity procured in the 2024 summer auctions. The aim of this chart is not to compare absolute volumes across DSOs, as the level of market maturity in countries like GB and the Netherlands makes it inappropriate to directly compare their results with those of newly launched LFMs, still refining their market design and engaging BSPs. Moreover, the specific characteristics of each distribution network and the diversity of design approaches adopted by different DSOs make it difficult to draw direct comparisons even within the same country. Instead, the purpose of this figure is to provide a snapshot of the current status of LFMs development across Europe, highlighting the level of service procurement achieved so far. For the Sthlmflex project, volumes are not reported, as the data was removed from the NODES platform following the project's conclusion and is currently not publicly available.

Fig. 12 shows the average availability and utilisation prices of accepted offers in the British LFMs,[1] as well as the average activation prices paid by Dutch DSOs on the GOPACS platform (only Liander, Enexis Netbeheer, and Stedin have issued calls to date). The focus is limited to GB and the Netherlands, as these are the only contexts with a sufficiently mature market design and volume of accepted offers to support meaningful economic analysis. It is important to note that the average price values reported for ENW are significantly higher than those of the other five British DSOs, due to low market liquidity during the analyzed year, as shown in Fig. 11. In this context, some resources took advantage of the limited competition to submit very high bids, with offered and accepted price peaks reaching around 11′000€/MW/h for availability and 7′000€/MWh for actual activation. Data from the other LFMs analyzed are reported, where available. In Slovenia, the average utilisation price is reported to be 0.60€/kWh. In Italy, the economic results from the early phases of the pilot projects are highly heterogeneous. For E-distribuzione, the weighted average availability price based on contracted capacity in the initial 2024 auctions is 863€/MW/h. The weighted average utilisation price, based on activated capacity, was close to the price cap of 500€/MWh. However, this figure is not particularly representative due to the very limited number of service activations that actually took place in 2024. For Areti and Unareti, the availability prices recognized to contracted capacity are significantly lower, with a weighted average of approximately 3€/MW/h for accepted offers in forward markets, and a weighted average utilisation price, based on activated capacity in spot markets, ranging between €200 and €300/MWh. No economic results were found for the auctions in France and Portugal.

4. Stakeholder participating in LFMs interviews

To complement the overview of the active European LFMs, a series of structured interviews was conducted with key stakeholders directly involved in these markets. A total of 16 interviews were carried out, including 6 DSOs, 7 BSPs, and 3 MPOs from various European countries. Stakeholders were selected based on their active participation in existing LFMs, pilot projects, or operational schemes. Beyond stakeholders operating in Italy, participants from GB, Switzerland, Slovenia, Sweden, and Portugal also participated.

Each stakeholder group was interviewed individually using a standardized questionnaire (reported in the Appendix) to ensure consistency, enable comparison across responses, and promote openness while minimizing response bias. The questions addressed the regulatory, technical, and operational dimensions of LFMs. The questionnaire was carefully structured to elicit comprehensive insights into the perceived enablers and barriers to effective market participation, aiming to capture each stakeholder group's overall perspective on the strengths of current LFM implementations and the key developments needed to enhance their effectiveness in the near future. The covered thematic areas included regulatory and administrative barriers, technical and operational challenges, market design features, and economic viability. In particular, for DSOs, the questions focused on *procurement mechanisms*, *auction design*, *unit activation procedures*, and *coordination with TSOs*. BSPs were asked about the *regulatory transparency*, *technological entry barriers* (e.g., metering requirements and automation needs), *communication systems*, *portfolio optimization strategies*, and *remuneration adequacy*. Finally, MPOs were consulted on issues related to *user accessibility*, *data management and security*, *market clearing mechanisms*, *platform scalability and interoperability*, and *regulatory compliance*. All stakeholder groups were also invited to reflect on national framework differences, identify areas for improvement, and comment on the role of LFMs in facilitating the integration of RESs.

All interviews were conducted via video calls, allowing for interactive discussion and clarification of responses. The analysis of the collected material was performed in two stages. In the first stage, the authors systematically reviewed and re-elaborated the responses, merging recurring viewpoints while highlighting divergences to preserve the full variety of perspectives. This was done separately for each stakeholder group, in order to reflect their specific roles and experiences. The following sections (4.1, 4.2, 4.3) present the main insights from this group-based analysis.

In the second stage, a comparative analysis was carried out across all stakeholder groups. Section 4.4 presents this synthesis, aimed at identifying both commonalities and differences in perspectives. Specifically, to provide a concise and comparative snapshot of stakeholders' views on current barriers to LFM development, a *quali-quantitative* assessment was conducted. Based on the perspectives summarized for each group, different aspects of LFMs were graded by the authors on a 1–5 scale, indicating the perceived strength of each barrier.

4.1. DSOs

A central theme emerging from the DSO interviews is the complexity of integrating LFMs into distribution network operations. While DSOs unanimously acknowledge the potential of LFMs to address local grid constraints, their widespread adoption is hindered by technical, regulatory, and operational challenges. Concerns raised by DSOs may be grouped into three categories: temporal and spatial effectiveness of LFMs market products; correct settlement of provided flexibility; and digital assets and platforms available for DERs monitoring and control. These issues are addressed in detail in the following paragraphs.

Italian DSOs noted that the procurement schemes adopted in the first year of their pilot projects (which were based on a single flexibility product with fixed availability windows and price caps) could fail to reflect the local and temporal variability of grid needs. Another key challenge reported by all DSOs is the need to define flexibility perimeters that accurately reflect their highly localized needs while ensuring sufficient market participation. Although high spatial granularity helps target specific grid issues (e.g., congestion), DSOs have noted that it often does not align with the actual distribution of DERs currently capable of offering services. This mismatch can reduce market liquidity, limit BSP participation, and ultimately weaken the effectiveness of LFMs.

In parallel with these design challenges, DSOs also raised concerns around the methodologies used to quantify delivered flexibility, particularly the definition and validation of baseline methodologies. Several interviewees pointed out that inaccurate or manipulable baselines can compromise both the remuneration of BSPs and the effective evaluation of system benefits. As emerged from the interviews, DSOs are exploring advanced solutions, including machine learning algorithms and digital twins [142] to improve baseline reliability and transparency.

Another critical technical bottleneck, which emerged in all the interviews, is the limited observability of distribution networks. Indeed, some DSOs emphasized the difficulty of managing flexibility without advanced monitoring systems, highlighting that the existing digital infrastructure and the current deployment of smart meters [143] and Distributed Energy Resource Management Systems (DERMS) [144] are not yet sufficient to enable real-time and high-resolution monitoring of network conditions. Where available, these tools are still under development or not yet fully integrated, leading DSOs to rely on static models or historical data, reducing the responsiveness and precision of flexibility activations. The activation procedure is another relevant issue. It is currently mainly manual and reliant on phone calls, emails, or SMS. This common practice among DSOs introduces delays and reduces the reliability of dispatching orders. Although some DSOs are experimenting API-based integrations and digital platforms, these efforts are still insufficient and slowed down by a lack of technical standards and interoperability requirements.

A final issue emerging from the interviews is the weak coordination

[1] Prices for GB have been converted to euros using the average 2024 exchange rate between the pound sterling and the euro (0.847 £/€ [150]).

between DSOs and TSOs. In most cases, the activation of flexibility resources is handled separately by both system operators, with limited data sharing and no shared framework for prioritizing activations. Interviewees emphasized the urgent need for regulatory intervention to define clear and formalized coordination mechanisms between DSOs and TSOs. Currently, while the importance of coordination is widely acknowledged, responsibility for its implementation is largely left to DSOs, who often lack the necessary tools and visibility over the transmission system to manage it effectively. Some DSOs proposed that LFMs could serve as a qualification platform for DERs seeking to participate in global flexibility markets. This approach would improve transparency, streamline the qualification processes of resources for both DSOs and the TSO, and enhance the economic attractiveness of flexibility services for DERs, ultimately increasing BSPs participation and contributing to greater LFM liquidity.

Despite these challenges, DSOs across Europe continue to have a strong interest in the evolution of LFMs. Many are actively participating in pilot projects and regulatory sandboxes that explore diversified procurement models, including multi-temporal auctions, hybrid remuneration schemes, and seasonal contracts [145,146]. These initiatives are driven by growing evidence that LFMs represent the most viable and cost-efficient solution to managing local grid congestions, offering an effective alternative to traditional grid reinforcement.

Looking ahead, all DSOs identified two main priorities for the future development of LFMs. First, on the technical side, there is a clear need to improve automation, real-time control, and monitoring at all levels. Second, on the regulatory side, progress is required to support effective coordination among system operators and BSPs, define standard baseline methodologies, and establish common digital protocols to ensure compatibility across different platforms and markets. These developments are considered fundamental to evolve LFMs from isolated pilot initiatives into fully integrated mechanisms in the European electricity system.

4.2. BSPs

A relevant concern emerging from BSP interviews is the economic viability of LFMs. Revenue unpredictability in less mature LFMs is cited as a major obstacle to the development of reliable business models. BSPs pointed to the uncertainty regarding the number of flexibility activations and the limited visibility into DSOs' local flexibility needs, which are often communicated with little advance notice. This narrow foresight makes it difficult for BSPs to estimate potential economic returns, preventing investments in technologies necessary to deliver flexibility. To address these issues, BSPs stressed the importance of availability-related remunerations, even at the expense of utilisation payments, which remain a more uncertain revenue stream, particularly during pilot phases of new LFMs. Moreover, they requested DSOs to publish three or five-year outlooks about their local flexibility needs. Furthermore, the need of developing revenue-sharing mechanisms involving other stakeholders, such as end-users and intermediaries like EV charging point operators, adds an additional layer of complexity that can discourage investments. Conversely, when market conditions are more transparent and DSO's intention to procure and utilize local flexibility is clearly communicated (e.g., in GB), BSPs reported that market participation became economically viable.

Looking at the economic domain, all BSPs agreed that a market-based approach is the most effective for procuring local flexibility services. However, some stressed that such markets should be complemented by additional measures, such as dynamic tariffs not only on energy prices but also on network charges, and specific availability contracts in cases where low liquidity constitutes an obstacle for the proper functioning of LFMs.

Another aspect that BSPs highlighted is the technical dimension of LFMs. First, it is noted that interoperability and automation capabilities remain uneven across the interviewed BSPs. In some of the countries involved in LFMs, the use of automation is very limited, mainly because the low economic opportunities prevent investments in monitoring and automation tools. As a result, participating BSPs tend to engage in LFMs using conventional commercial or industrial generation units, where on-site operators can manually adjust the power output of contracted resources. Moreover, DSO activations are largely manual, as already highlighted, making it more difficult for BSPs to dispatch their units automatically. Oppositely, in some countries like GB, BSPs reported being able to automatically control their units by leveraging optimization strategies based on locational market prices and forecasted grid needs. Similarly, in Switzerland, BSPs have reported beginning to adopt cloud-to-cloud communication systems and to explore advanced protocols such as MODBUS-TCP for distributed asset control.

Technical requirements (e.g., minimum bid sizes and service duration) are generally judged to be acceptable. As highlighted by BSPs, the main barrier is the need to deploy very expensive field-level instrumentation and metering systems even for small resources. For instance, user interfaces have been labeled as usually costly and inefficient, discouraging newcomers from joining the market.

The regulatory landscape is widely recognized as fragmented and unclear, often presenting a barrier for BSPs who are unfamiliar with these new initiatives. Specifically, it was noted that Italy lacks a national platform where various LFM initiatives are clearly explained, and where BSPs can access information on economic remuneration schemes and participation rules. Italian BSPs also suggested standardizing the three pilot projects currently active in the country, advocating for a unified market platform with consistent participation rules. This corresponds to what has been done in other countries, such as GB, where DSOs were given the freedom to design their LFMs within a well-defined framework of common rules. Additionally, some BSPs highlighted the reduced size of flexibility perimeters, sometimes limited to only a few streets or a neighborhood, which makes scalability unfeasible.

Future developments suggested by BSPs include a revision of baseline calculation methodologies, which are often inadequate to represent the reference power profile for certain types of users, such as PV systems, HPs, or EVs. More advanced tools, such as machine learning models that go beyond purely historical data, were proposed as more appropriate alternatives and should be allowed by DSOs. Moreover, BSPs emphasized that significant work is still needed to properly integrate the outcomes of LFMs into electricity spot markets, particularly from a regulatory perspective in terms of commercial exchanges between BSPs and BRPs.[2] Finally, some BSPs expressed interest in expanding their service offerings beyond active power regulation to include services such as reactive power support, islanding, and black start capabilities.

4.3. MPOs

The main goal of MPOs is to enable scalable, accessible, and reliable LFMs. According to interviewed MPOs, their platforms are already capable of handling volumes far greater than current levels. Additionally, security remains a key priority, with MPOs investing in robust infrastructures to ensure the confidentiality of data. At the same time, regulatory compliance is central, with some platforms strictly adhering to national regulations, while others are evolving to meet emerging EU directives. Moreover, the minimal number of service disruptions reported by the MPOs highlights the reliability of operating platforms. Many MPOs have also reported to be engaged in pilot projects, often in collaboration with DSOs, TSOs, and research institutions, to test innovative market designs and further enhance platform capabilities.

Another aspect that the interviews revealed is the different strategies

[2] Balance Responsible Parties (BRPs), as defined in the European guideline on electricity balancing, are market participants responsible for ensuring that their electricity injections and withdrawals of their units are balanced within each market time unit [26].

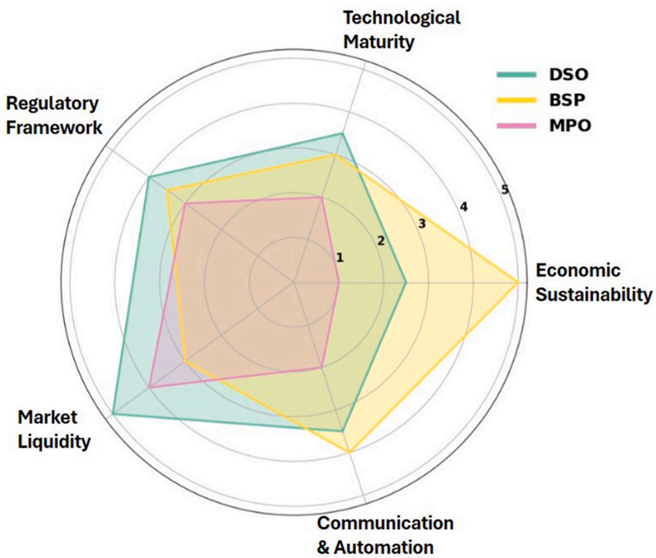

Fig. 13. Radar chart illustrating the perceived impact of five key barriers limiting large-scale deployment of LFMs, reported separately by different stakeholders (DSOs, BSPs, MPOs).
Values are based on stakeholder interviews and interpreted by the authors employing a *quali-quantitative* approach, where a score of 5 indicates that the corresponding LFM dimension is viewed as a major barrier, and a score of 1 means it is not considered problematic. Economic sustainability is perceived as the primary barrier by BSPs, while DSOs identify market liquidity, closely linked to technological maturity challenges, as the current main obstacle. Regulatory fragmentation is recognized as a significant issue by all three stakeholder groups.

among MPOs regarding the integration of LFMs with national electricity markets. Several MPOs highlighted the importance of such integration to ensure consistency and efficiency across market layers. For instance, as discussed in previous chapters, in Italy, GME has developed a new section of its existing national market platform dedicated to LFMs [147], using the same web infrastructure employed for other markets, simplifying participant access. Instead, Piclo is pursuing integration through PicloMax [148], a service initially launched in GB and now expanding in more countries, designed to link LFMs with broader electricity markets and to enhance interoperability across different national market frameworks. These distinct strategies reflect both the different levels of market maturity and the regulatory framework in which platforms operate, as well as a shared need for deeper market integration.

Despite the differences in platform structure, one consistent priority across all MPOs is user experience, particularly for smaller or less experienced BSPs. This goal is pursued through several concrete measures, such as streamlining participation procedures, offering intuitive user interfaces, providing clear documentation, and delivering onboarding support or training resources.

According to interview feedback, several challenges continue to hinder the scalability and broader adoption of LFMs. These include limited market liquidity, high technical complexity, and fragmented regulatory frameworks, both within countries and across national borders. To address these barriers, MPOs are actively working to improve market transparency, refine market-clearing algorithms, and enhance platform accessibility. Increasing attention is also being devoted to cross-border coordination and effective integration with national energy systems. As the regulatory landscape evolves, aligning MPO platforms with both national and EU-level policy developments remains a strategic priority.

4.4. Comparative analysis of stakeholder perspectives

Fig. 13 provides a visual representation of the key barriers to the widespread adoption of LFMs in Europe, as perceived by the interviewed stakeholders. It identifies five dimensions that influence the development of LFMs: *regulatory framework*, *technological maturity*, *economic feasibility*, *communication and automation*, and *market liquidity*. The quantification shown in Fig. 13 is the result of a *quali-quantitative* approach, in which each dimension was graded from 1 to 5 based on both the number of interviewees who identified it as critical and the degree of criticality they attributed to it.

The regulatory framework clearly stands out as a significant barrier across all stakeholder groups. From the perspective of BSPs, the lack of a consistent national or EU-level regulatory reference creates uncertainty and makes it more difficult to approach LFM initiatives. For DSOs, regulatory fragmentation leads to various operational challenges, such as weak coordination with the TSO. Meanwhile, MPOs struggle to adapt their platforms to heterogeneous national rules, complicating scalability and integration efforts.

Technological maturity presents challenges for both DSOs and BSPs. On the DSO side, some operators lack a sufficiently dense deployment of metering and monitoring infrastructure, which is necessary to enable more automated and efficient service activation methods. On the other hand, BSPs often interact with DERs that are equipped with limited communication interfaces, such as outdated inverters, which hinder remote control capabilities and automated dispatch.

Economic feasibility is a critical issue, particularly for BSPs. In contexts where many DERs are not originally designed for flexible operation, the revenues from LFM participation are currently insufficient to justify investments in additional control or automation equipment. As a result, many BSPs are only able to offer flexibility through manual interventions, which significantly limits scalability.

The dimension of communication and automation, closely related to the previous two, also presents barriers, especially for DSOs and BSPs. High costs associated with enabling real-time, secure communication across distributed assets can discourage the deployment of automated flexibility solutions, particularly when the economic returns are uncertain or marginal.

Finally, market liquidity emerges as a universal challenge for all stakeholders. For DSOs, low participation rates undermine the effectiveness of LFMs as a tool to solve local grid issues, which may result in sunk costs and unaddressed operational needs. For MPOs, platform development and maintenance only become viable when there is sufficient user engagement and transaction volume. BSPs, in turn, are unable to properly assess the economic viability or technical challenges of their flexible assets without a meaningful level of market activity.

5. Conclusions

This work provides an overview of LFMs across Europe, addressing the technical, regulatory and economic challenges associated with their widespread adoption in power distribution networks. Both the literature review and the analyzed case studies confirm that LFMs are a highly relevant and timely topic, with pilot and operational initiatives now present in most of the European countries.

The literature shows that several aspects of LFMs design remain contested. Forward auctions are generally considered the most suitable option in the early stages of LFM development, particularly if flexibility is procured as an alternative to network reinforcement. They provide DSOs with greater planning security and lower entry barriers for BSPs. As LFMs mature, however, short-term markets become increasingly relevant, fostering competition and enabling the procurement of services for emergency conditions that cannot be anticipated in advance. In parallel, studies highlight the need to move beyond uniform pricing toward locational pricing, which more accurately captures the impact of flexibility on congestion management and voltage regulation. With respect to service typology, research is gradually expanding beyond the current focus on active power management to analyze the local procurement of voltage support and emergency services. On the technology side, the potential of BESS, EVs, and DR is consistently emphasized, as these resources are well-suited to deliver the flexibility DSOs require. By contrast, the future electrification of industry and the transformation of district heating systems remain comparatively underexplored, despite their clear relevance as new sources of flexibility within a sector-coupling perspective. Regarding TSO–DSO coordination, most studies highlight the benefits of centralized approaches, in which the TSO optimizes system operations and DSOs implement the resulting dispatch. Regardless of the chosen coordination model, however, secure and efficient data exchange between system operators emerges as a critical challenge, with cloud-based platforms frequently proposed as enabling solutions. Finally, in the area of DSO-BSP communication, the dominant concerns are cybersecurity and data privacy, with blockchain technologies widely investigated as potential tools to ensure transparency and resilience in LFM transactions and service activations.

The case studies analyzed in this review confirm the heterogeneity of current LFM designs in Europe. Markets differ in their reliance on forward or spot procurement, in their product definitions, and in their remuneration and settlement mechanisms. In particular, baseline methodologies for service validation remain an unresolved issue: experiences show that no single approach is suitable for all technologies and aggregation levels. Service activation, by contrast, is more homogeneous, often relying on simple communication tools such as SMS or email, though there is a clear trend toward API-based solutions. The degree of market maturity also varies significantly. The next few years will be crucial to transition from pilot projects, such as those currently underway in Italy and Portugal, toward fully developed and large-scale markets, as already implemented in countries like GB and the Netherlands.

Insights from the stakeholder interviews further highlight the actions needed to support LFM development. First, a stronger regulatory commitment is needed to harmonize the fragmented experiences that currently exist at the European level. A more uniform framework would reduce the variability of LFMs deployed by different DSOs, which is currently a significant barrier to broader BSP participation. Particularly, regulatory efforts should prioritize the definition of a shared framework for flexibility products and baseline methodologies within LFMs, taking inspiration from the British context, where a broad portfolio of products and well-established baseline methodologies have been successfully adopted for several years. Moreover, a coordinated regulatory effort could produce common guidelines to enable effective cooperation between DSOs and TSOs—a key requirement for managing the simultaneous activation of local and global flexibility services—and to better integrate local market platforms into national and pan-European electricity markets, an area where MPOs are well-positioned to act as enablers. In this regard, the forthcoming Network Code on Demand Response (DR NC) appears to be the EU's expected vehicle for harmonization. Proposed by ENTSO-E and the EU DSO Entity, the DR NC foresees [149]: (i) common national terms and conditions covering DER aggregation models, baselining, the national flexibility register, local market design, and TSO–DSO coordination; and (ii) Union-wide provisions, such as standardized product attribute lists and technical requirements for metering devices, subject to ACER approval. These measures directly target the main regulatory gaps highlighted in this review and, if consistently enforced, could establish the regulatory foundation for a more coherent and scalable implementation of LFMs across Europe.

In parallel, stakeholders highlight how investments are needed to upgrade the monitoring infrastructure of distribution networks, including LV grids, and to support the development of advanced grid management software capable of fully harnessing the potential of LFMs and the growing penetration of DERs. At the same time, targeted incentives should be introduced to support BSPs during this early stage, enabling them to establish the necessary communication and automation infrastructure for delivering flexibility from both generation and consumption units. Without such measures, flexibility provision is likely to remain limited to medium- and large-scale units with manual control capabilities, often inadequate for addressing the highly localized operational needs of DSOs. To unlock the full potential of LFMs, however, it is essential to harness flexibility from all technologies. In particular, aggregated residential consumers, still largely untapped in less mature LFMs, represent a promising avenue for enhancing market liquidity and ensuring more widespread flexibility availability across distribution networks.

In conclusion, while LFMs represent a promising tool for addressing the growing complexity of electricity distribution systems and accelerating the integration of DERs, their widespread adoption is not guaranteed and will require a coordinated effort from regulatory bodies, system operators and market participants. By aligning technical standards, regulatory frameworks, and investment priorities, Europe can move from isolated pilot initiatives to cohesive, scalable, and impactful LFMs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

The questionnaires referenced in Chapter 4 are accessible online: https://doi.org/10.1016/j.rser.2025.116434.

Data availability

Data will be made available on request.

References

[1] Butenko A, Cseres K. The regulatory consumer: prosumer-driven local energy production initiatives. SSRN Electron J Nov. 2015. https://doi.org/10.2139/SSRN.2631990.

[2] IEA. Empowering people – the role of local energy communities in clean energy transitions. Paris, https://www.iea.org/commentaries/empowering-people-the-role-of-local-energy-communities-in-clean-energy-transitions. [Accessed 1 April 2025].

[3] SolarPower Europe. EU market outlook for solar power 2024-2028 [Online]. Available: https://www.solarpowereurope.org/insights/outlooks/eu-market-outlook-for-solar-power-2024-2028/detail. [Accessed 17 March 2025].

[4] IEA. Number of EVs, air conditioners, and heat pumps in operation in the stated policies scenario, 2023 and 2035 – charts – Data & statistics [Online]. Available: https://www.iea.org/data-and-statistics/charts/number-of-evs-air-conditioners-and-heat-pumps-in-operation-in-the-stated-policies-scenario-2023-and-2035. [Accessed 1 April 2025].

[5] European heat pump association, "Market data." [Online]. Available: https://www.ehpa.org/market-data/. [Accessed 17 March 2025].

[6] IEA. Trends in electric cars – Global EV outlook 2024 [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2024/trends-in-electric-cars. [Accessed 17 March 2025].

[7] Eurostat. Final energy consumption in industry - detailed statistics [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title

=Final_energy_consumption_in_industry_-_detailed_statistics. [Accessed 1 October 2025].
[8] Clean industrial deal - european commission. https://commission.europa.eu/topics/eu-competitiveness/clean-industrial-deal_en. [Accessed 1 October 2025].
[9] Commision European. Study on the effective integration of distributed energy resources for providing flexibility to the electricity system [Online]. Available: https://energy.ec.europa.eu/publications/study-effective-integration-distributed-energy-resources-providing-flexibility-electricity-system_en. [Accessed 27 March 2025].
[10] IEA. Unlocking the potential of distributed energy resources - Power system opportunities and best practices. Paris, https://www.iea.org/reports/unlocking-the-potential-of-distributed-energy-resources. [Accessed 18 March 2025].
[11] International Renewable Energy Agency. Innovation landscape brief: behind-the-meter batteries. Abu Dhabi, www.irena.org. [Accessed 1 April 2025].
[12] Filho WL, et al. Prosumers and sustainable development: an international assessment in the field of renewable energy. Sustain Feature Jun. 2024;7:100158. https://doi.org/10.1016/J.SFTR.2024.100158.
[13] Zachmann G, et al. Decarbonisation of energy: determining a robust mix of energy carriers for a carbon-neutral EU. Berlin: Deutsches Institut für Wirtschaftsforschung (DIW); 2021. Berlin, https://www.econstor.eu/handle/10419/251795. [Accessed 1 April 2025].
[14] Kotsonias A, Hadjidemetriou L, Asprou M, Panayiotou CG. Operational challenges and solution approaches for low voltage distribution grids — a review. Elec Power Syst Res Feb. 2025;239:111258. https://doi.org/10.1016/J.EPSR.2024.111258.
[15] IEA. Electricity grids and secure energy transitions - enhancing the foundations of resilient, sustainable and affordable power systems. Paris, https://www.iea.org/reports/electricity-grids-and-secure-energy-transitions. [Accessed 18 March 2025].
[16] Daccò E, et al. Forecasting methodologies of the electrical load in urban distribution networks: a case study in Milan, Italy. In: Proceedings - 2023 IEEE international conference on environment and electrical engineering and 2023 IEEE industrial and commercial power systems Europe, EEEIC/I and CPS Europe 2023; 2023. https://doi.org/10.1109/EEEIC/ICPSEUROPE57605.2023.10194858.
[17] Bovera F, Schiavo L Lo, Vailati R. Combining forward-looking expenditure targets and fixed OPEX-CAPEX shares for a future-proof infrastructure regulation: the ROSS approach in Italy. Curr Sustain Renew Energy Rep Dec. 2024;11(4):105–15. https://doi.org/10.1007/S40518-024-00239-4.
[18] Daccò E, Falabretti D, Ilea V, Merlo M, Nebuloni R, Spiller M. Decentralised voltage regulation through optimal reactive power flow in distribution networks with dispersed generation. Electricity Mar. 2024;5(1):134–53. https://doi.org/10.3390/ELECTRICITY5010008. 2024, Vol. 5, Pages 134-153.
[19] Energy Networks Association (ENA). ON21-PRJ open networks flexibility connections explainer and Q&A (19 Aug 2021) [Online]. Available: https://www.energynetworks.org/publications/on21-prj-open-networks-flexibility-connections-explainer-and-q-and-a-(19-aug-2021. [Accessed 18 March 2025].
[20] Viola L, Mohammadi S, Dotta D, Hesamzadeh MR, Baldick R, Flynn D. Ancillary services in power system transition toward a 100% non-fossil future: market design challenges in the United States and Europe. Elec Power Syst Res Nov. 2024;236:110885. https://doi.org/10.1016/J.EPSR.2024.110885.
[21] Silva R, et al. Characterization of TSO and DSO grid system services and TSO-DSO basic coordination mechanisms in the current decarbonization context. Energies Jul. 2021;14(15):4451. https://doi.org/10.3390/EN14154451. 2021, Vol. 14, Page 4451.
[22] Greenwood Oakley. Cost-benefit analysis of a possible demand response mechanism [Online]. Available: https://www.aemc.gov.au/sites/default/files/content/0010bfe5-a8ce-47f9-b22d-e4c1d4d93737/Attachment-A.pdf. [Accessed 27 May 2025].
[23] Gorenstein Dedecca J, Ansarin M, Bene C, Van Delzen T, Van Nuffel L, Jagtenberg H. Increasing flexibility in the EU energy system - technologies and policies to enable the integration of renewable electricity sources. Mar. 2025. Luxembourg, https://www.europarl.europa.eu/thinktank/en/document/ECTI_STU(2025)769347.
[24] Chondrogiannis S, Vasiljevska J, Marinopoulos A, Papaioannou I, Flego G. Local electricity flexibility markets in Europe. 2022. https://doi.org/10.2760/9977. Luxembourg.
[25] ENTSO-E and Frontier Economics Ltd, "REVIEW OF FLEXIBILITY PLATFORMS," 2021. Accessed: May 27, 2025. [Online]. Available: https://eepublicdownloads.azureedge.net/clean-documents/SOC%20documents/SOC%20Reports/210957_entso-e_report_neutral_design_flexibility_platforms_04.pdf.
[26] European Commission, "Commission regulation (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing." Accessed: March. 27, 2025. [Online]. Available: https://eur-lex.europa.eu/eli/reg/2017/2195/oj/eng.
[27] Energy Networks Association (ENA), "ON18-WS1A flexibility commitment 2018." Accessed: March. 18, 2025. [Online]. Available: https://www.energynetworks.org/publications/on18-ws1a-flexibility-commitment-2018.
[28] GOPACS - platform for congestion management." Accessed: March. 17, 2025. [Online]. Available: https://www.gopacs.eu/en/.
[29] DIRECTIVE (EU) 2019/944 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL - of 5 June 2019 - on common rules for the internal market for electricity and amending directive 2012/27/EU." [Online]. Available: https://eur-lex.europa.eu/eli/dir/2019/944/oj/eng.
[30] How to provide Local Flexibility Services | enedis." Accessed: March. 17, 2025. [Online]. Available: https://www.enedis.fr/co-building-dso-local-flexibility.
[31] Svenska kraftnät, "sthlmflex." Accessed: March. 18, 2025. [Online]. Available: https://www.svk.se/sthlmflex.
ARERA, "Delibera 03 agosto 2021 352/2021/R/eel." Accessed: March. 17, 2025. [Online]. Available: https://www.arera.it/atti-e-provvedimenti/dettaglio/21/352-21.
[33] E-Distribuzione, "Il progetto EDGE." Accessed: March. 18, 2025. [Online]. Available: https://www.e-distribuzione.it/progetti-e-innovazioni/il-progetto-edge.html.
[34] Areti, "Progetto RomeFlex." Accessed: March. 18, 2025. [Online]. Available: https://www.areti.it/conoscere-areti/innovazione/progetto-romeflex.
[35] Unareti, "Sperimentazione MiNDFlex per la rete elettrica di Milano." Accessed: March. 18, 2025. [Online]. Available: https://www.unareti.it/it/media/progetti/sperimentazione-mindflex-rete-elettrica-milano.
[36] E-REDES, "FIRMe - integrated flexibility in a market regime." Accessed: March. 18, 2025. [Online]. Available: https://www.e-redes.pt/en/energy-transition/firme.
[37] Elektro Ljubljana, "Annual report 2023." Accessed: March. 31, 2025. [Online]. Available: https://www.elektro-ljubljana.si/Portals/0/Za-delnicarje/Elektro_Ljubljana_2023_LetnoPorocilo_EN.pdf.
[38] Jin X, Wu Q, Jia H. Local flexibility markets: literature review on concepts, models and clearing methods. Appl Energy Mar. 2020;261:114387. https://doi.org/10.1016/J.APENERGY.2019.114387.
[39] Valarezo O, et al. Analysis of new flexibility market models in Europe. Energies Jun. 2021;14(12):3521. https://doi.org/10.3390/EN14123521. 2021, Vol. 14, Page 3521.
[40] Gulotta F, Daccò E, Bosisio A, Falabretti D. Opening of ancillary service markets to distributed energy resources: a review. Energies Mar. 2023;16(6):2814. https://doi.org/10.3390/EN16062814. 2023, Vol. 16, Page 2814.
[41] Rebenaque O, Schmitt C, Schumann K, Dronne T, Roques F. Success of local flexibility market implementation: a review of current projects. Util Policy Feb. 2023;80:101491. https://doi.org/10.1016/J.JUP.2023.101491.
[42] Jimeno J, Madina C, Fernandez E, Aranzabal I, Gomez-Arriola I, Vicente-Figueirido I. Local flexibility markets in Europe: a review of flexibility products, services, and potential improvements. In: International conference on the European energy market. EEM; 2025. https://doi.org/10.1109/EEM64765.2025.11050255.
[43] Viganò G, Lattanzio G, Rossi M. Review of main projects, characteristics and challenges in flexibility markets for services addressed to electricity distribution network. Energies Jun. 2024;17(11):2781. https://doi.org/10.3390/EN17112781. 2024, Vol. 17, Page 2781.
[44] Bouloumpasis I, Mirzaei Alavijeh N, Steen D, Le AT. Local flexibility market framework for grid support services to distribution networks. Electr Eng Apr. 2022;104(2):401–19. https://doi.org/10.1007/S00202-021-01248-Y.
[45] Page MJ, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Br Med J Mar. 2021;372. https://doi.org/10.1136/BMJ.N71.
[46] Grid congestion is posing challenges for energy security and transitions – analysis - IEA." Accessed: May 9, 2025. [Online]. Available: https://www.iea.org/commentaries/grid-congestion-is-posing-challenges-for-energy-security-and-transitions.
[47] Technology options – introduction to system integration of renewables – analysis - IEA." Accessed: May 9, 2025. [Online]. Available: https://www.iea.org/reports/introduction-to-system-integration-of-renewables/technology-options.
[48] Ziras C, Zepter JM, Pechrak S, Tsaousoglou G. Designing a local flexibility market for buying back capacity from electricity consumers connected to the distribution network. Util Policy Apr. 2025;93:101889. https://doi.org/10.1016/J.JUP.2025.101889.
[49] Lustenberger M, Bellizio F, Cai H, Heer P, Ziras C. Introducing price feedback of local flexibility markets into distribution network planning. Elec Power Syst Res Nov. 2024;236:110686. https://doi.org/10.1016/J.EPSR.2024.110686.
[50] Nolden C, Banks N, Irwin J, Wallom D, Parrish B. The economics of flexibility service contracting in local energy markets: a review. Renew Sustain Energy Rev Jun. 2025;215:115549. https://doi.org/10.1016/J.RSER.2025.115549.
[51] Ramos A, De Jonghe C, Gómez V, Belmans R. Realizing the smart grid's potential: defining local markets for flexibility. Util Policy Jun. 2016;40:26–35. https://doi.org/10.1016/J.JUP.2016.03.006.
[52] Michaelis A, Schneider M, Weibelzahl M. Designing local flexibility markets: a toolbox for policymakers and market operators. Energy Aug. 2025;329:136051. https://doi.org/10.1016/J.ENERGY.2025.136051.
[53] van de Water PR, Doumen SC, Campfens JKEK, Wieczorek AJ, Nguyen PH. An implementation pathway for price formation mechanisms in local electricity markets. Energy Rep Jun. 2025;13:6384–96. https://doi.org/10.1016/J.EGYR.2025.05.026.
[54] Wang L, Jacobs M, Austnes PF, Paolone M. Local market-aware optimal allocation of energy storage systems considering price fairness in power distribution networks. Sustain Energy Grid Netw Jun. 2025;42:101648. https://doi.org/10.1016/J.SEGAN.2025.101648.
[55] Mehinovic A, Suljanovic N, Zajc M. Quantifying the impact of flexibility asset location on services in the distribution grid: power system and local flexibility market co-simulation. Elec Power Syst Res Jan. 2025;238:111037. https://doi.org/10.1016/J.EPSR.2024.111037.
[56] Taromboli G, Soares T, Villar J, Zatti M, Bovera F. Impact of different regulatory approaches in renewable energy communities: a quantitative comparison of European implementations. Energy Policy Dec. 2024;195:114399. https://doi.org/10.1016/J.ENPOL.2024.114399.

[57] Taxt H, et al. Integration of energy communities in distribution grids: development paths for local energy coordination. Energy Strategy Rev Mar. 2025; 58:101668. https://doi.org/10.1016/J.ESR.2025.101668.
[58] García-Muñoz F, Farriol A, Eichman J. Statistical analysis of an energy community's operations in P2P energy trading and flexibility markets. Sustain Energy Grid Netw Sep. 2025;43:101755. https://doi.org/10.1016/J.SEGAN.2025.101755.
[59] Zhang W, Zavala VM. Remunerating space–time, load-shifting flexibility from data centers in electricity markets. Appl Energy Nov. 2022;326:119930. https://doi.org/10.1016/J.APENERGY.2022.119930.
[60] Berg B, et al. Occupant-driven end use load models for demand response and flexibility service participation of residential grid-interactive buildings. J Build Eng Nov. 2024;96:110406. https://doi.org/10.1016/J.JOBE.2024.110406.
[61] Kalogeropoulos I, Sarimveis H. Predictive control algorithms for congestion management in electric power distribution grids. Appl Math Model Jan. 2020;77:635–51. https://doi.org/10.1016/J.APM.2019.07.034.
[62] Liere-Netheler I, Schuldt F, von Maydell K, Agert C. Optimised curtailment of distributed generators for the provision of congestion management services considering discrete controllability. IET Gener, Transm Distrib Mar. 2020;14(5):735–44. https://doi.org/10.1049/IET-GTD.2019.0992.
[63] Spiliotis K, Claeys S, Gutierrez AR, Driesen J. Utilizing local energy storage for congestion management and investment deferral in distribution networks. In: International conference on the European energy market, EEM; 2016-July. https://doi.org/10.1109/EEM.2016.7521198. Jul. 2016.
[64] ENTSO-E, "Network code for requirements for grid connection applicable to all generators." Accessed: April. 17, 2025. [Online]. Available: https://eepublicdownloads.entsoe.eu/clean-documents/pre2015/resources/RfG/130308_Final_Version_NC_RfG.pdf.
[65] ENTSO-E, "IMPLEMENTATION GUIDELINE FOR NETWORK CODE 'requirements for grid connection applicable to all generators.'" Accessed: April. 17, 2025. [Online]. Available: https://eepublicdownloads.entsoe.eu/clean-documents/pre2015/resources/RfG/131016_-_NC_RfG_implementation_guideline.pdf.
[66] Canizes B, Silveira V, Vale Z. Demand response and dispatchable generation as ancillary services to support the low voltage distribution network operation. Energy Rep Jun. 2022;8:7–15. https://doi.org/10.1016/J.EGYR.2022.01.040.
[67] Han D, Koo D, Shin C, Won D. Hierarchical robust day-ahead VPP and DSO coordination based on local market to enhance distribution network voltage stability. Int J Electr Power Energy Syst Sep. 2024;160:110076. https://doi.org/10.1016/J.IJEPES.2024.110076.
[68] Yumiki S, et al. Autonomous vehicle-to-grid design for provision of frequency control ancillary service and distribution voltage regulation. Sustain Energy Grid Netw Jun. 2022;30:100664. https://doi.org/10.1016/J.SEGAN.2022.100664.
[69] Anany MG, ElDesouky AA, Salem AA. Real-time V2G simulator for grid system frequency and voltage regulation with fault ride-through capabilities. Elec Power Syst Res Sep. 2024;234:110561. https://doi.org/10.1016/J.EPSR.2024.110561.
[70] Zhang S, Mishra Y, Shahidehpour M. Utilizing distributed energy resources to support frequency regulation services. Appl Energy Nov. 2017;206:1484–94. https://doi.org/10.1016/J.APENERGY.2017.09.114.
[71] Daccò E, Falabretti D, Vicario A. Intentional islanding of active distribution networks by GenSets: an analysis of technical constraints and opportunities. Int Trans Electr Energy Syst Jan. 2023;2023(1):3048966. https://doi.org/10.1155/2023/3048966.
[72] Li X, et al. Research on the integration of mobile energy storage system for enhancing black start capability and resilience in distribution networks under extreme events. Sustain Energy Grid Netw Sep. 2025;43:101724. https://doi.org/10.1016/J.SEGAN.2025.101724.
[73] Scrocca A, Bovera F, Delfanti M, Blaco A. Recursive reconfiguration of private MV networks to maximize dynamic islanding capability. In: 2024 116th AEIT international annual conference, AEIT 2024; 2024. https://doi.org/10.23919/AEIT63317.2024.10736814.
[74] Calderaro V, Milanovic JV, Kayikci M, Piccolo A. The impact of distributed synchronous generators on quality of electricity supply and transient stability of real distribution network. Elec Power Syst Res Jan. 2009;79(1):134–43. https://doi.org/10.1016/J.EPSR.2008.05.022.
[75] Salim RH, Kuiava R, Ramos RA, Bretas NG. Impact of power factor regulation on small-signal stability of power distribution systems with distributed synchronous generators. Eur Trans Electr Power Oct. 2011;21(7):1923–40. https://doi.org/10.1002/ETEP.504.
[76] Chalise S, Atia HR, Poudel B, Tonkoski R. Impact of active power curtailment of wind turbines connected to residential feeders for overvoltage prevention. IEEE Trans Sustain Energy Apr. 2016;7(2):471–9. https://doi.org/10.1109/TSTE.2015.2499775.
[77] Karimi M, Mokhlis H, Naidu K, Uddin S, Bakar AHA. Photovoltaic penetration issues and impacts in distribution network – a review. Renew Sustain Energy Rev Jan. 2016;53:594–605. https://doi.org/10.1016/J.RSER.2015.08.042.
[78] Prionistis G, Souxes T, Vournas C. Voltage stability support offered by active distribution networks. Elec Power Syst Res Jan. 2021;190:106728. https://doi.org/10.1016/J.EPSR.2020.106728.
[79] Prakash K, et al. A review of battery energy storage systems for ancillary services in distribution grids: current status, challenges and future directions. Front Energy Res Sep. 2022;10:971704. https://doi.org/10.3389/FENRG.2022.971704.
[80] Taltavull-Villalonga V, Bullich-Massagué E, Saldaña-González AE, Sumper A. Enhancing distribution grid efficiency and congestion management through optimal battery storage and power flow modeling. Electricity Jun. 2024;5(2):351–69. https://doi.org/10.3390/ELECTRICITY5020018. 2024, Vol. 5, Pages 351-369.
[81] Shafie-Khah M, Siano P, Fitiwi DZ, Mahmoudi N, Catalão JPS. An innovative two-level model for electric vehicle parking lots in distribution systems with renewable energy. IEEE Trans Smart Grid 2018;9(2):1506–20. https://doi.org/10.1109/TSG.2017.2715259.
[82] Alam MJE, Muttaqi KM, Sutanto D. Effective utilization of available PEV battery capacity for mitigation of solar PV impact and grid support with integrated V2G functionality. IEEE Trans Smart Grid May 2016;7(3):1562–71. https://doi.org/10.1109/TSG.2015.2487514.
[83] Siano P. Demand response and smart grids—A survey. Renew Sustain Energy Rev Feb. 2014;30:461–78. https://doi.org/10.1016/J.RSER.2013.10.022.
[84] Fotouhi Ghazvini MA, et al. Congestion management in active distribution networks through demand response implementation. Sustain Energy Grid Netw Mar. 2019;17:100185. https://doi.org/10.1016/J.SEGAN.2018.100185.
[85] Talaeizadeh V, Shayanfar H, Aghaei J. Enhancing energy and flexibility joint market clearing mechanism through TSO-DSO coordination. Elec Power Syst Res Jan. 2025;238:111162. https://doi.org/10.1016/J.EPSR.2024.111162.
[86] Vagropoulos SI, Biskas PN, Bakirtzis AG. Market-based TSO-DSO coordination for enhanced flexibility services provision. Elec Power Syst Res Jul. 2022;208:107883. https://doi.org/10.1016/J.EPSR.2022.107883.
[87] Nikkhah S, Rabiee A, Soroudi A, Allahham A, Taylor PC, Giaouris D. Distributed flexibility to maintain security margin through decentralised TSO–DSO coordination. Int J Electr Power Energy Syst Mar. 2023;146:108735. https://doi.org/10.1016/J.IJEPES.2022.108735.
[88] Esmaeel Nezhad A, Tavakkoli Sabour T, Joshi RP. Coordinated TSO-DSO operational planning for congestion management in day-ahead and real-time markets. e-Prime Adv Electr Eng Electron Energy Jun. 2025;12:100981. https://doi.org/10.1016/J.PRIME.2025.100981.
[89] Amjad M, Taylor G, Li M, Huang Z. A critical evaluation of cloud computing techniques for TSO and DSO information and data exchange. In: 2021 11th international conference on power and energy systems, ICPES 2021; 2021. p. 481–5. https://doi.org/10.1109/ICPES53652.2021.9683900.
[90] Radi M, Taylor G, Cantenot J, Lambert E, Suljanovic N. Developing enhanced TSO-DSO information and data exchange based on a novel use case methodology. Front Energy Res Jun. 2021;9:670573. https://doi.org/10.3389/FENRG.2021.670573.
[91] Wu Y, Wu Y, Cimen H, Vasquez JC, Guerrero JM. P2P energy trading: blockchain-enabled P2P energy society with multi-scale flexibility services. Energy Rep Nov. 2022;8:3614–28. https://doi.org/10.1016/J.EGYR.2022.02.074.
[92] Huang CT, Scott IJ. Peer-to-peer multi-period energy market with flexible scheduling on a scalable and cost-effective blockchain. Appl Energy Aug. 2024;367:123331. https://doi.org/10.1016/J.APENERGY.2024.123331.
[93] Li W, Tang R, Wang S, Zheng Z. An optimal design method for communication topology of wireless sensor networks to implement fully distributed optimal control in IoT-enabled smart buildings. Appl Energy Nov. 2023;349:121539. https://doi.org/10.1016/J.APENERGY.2023.121539.
[94] Dai S, Mansouri SA, Huang S, Alharthi YZ, Wu Y, Bagherzadeh L. A multi-stage techno-economic model for harnessing flexibility from IoT-enabled appliances and smart charging systems: developing a competitive local flexibility market using stackelberg game theory. Appl Energy Nov. 2024;373:123868. https://doi.org/10.1016/J.APENERGY.2024.123868.
[95] Gnana GS, Karthikeyan A, Karthikeyan K, Sanjeevikumar P, Karapparambil Thomas S, Babu A. Critical review of SCADA and PLC in smart buildings and energy sector. Energy Rep Dec. 2024;12:1518–30. https://doi.org/10.1016/J.EGYR.2024.07.041.
[96] Dangwal G, et al. An effective intrusion detection scheme for distributed network protocol 3 (DNP3) applied in SCADA-Enabled IoT applications. Comput Electr Eng Dec. 2024;120:109828. https://doi.org/10.1016/J.COMPELECENG.2024.109828.
[97] Rodriguez-Perez N, Domingo JM, Lopez GL, Stojanovic V. Scalability evaluation of a modbus TCP control and monitoring system for distributed energy resources. In: IEEE PES innovative smart grid technologies conference Europe; 2022. https://doi.org/10.1109/ISGT-EUROPE54678.2022.9960319. 2022-October.
[98] Schmutzler J, Wietfeld C, Andersen CA. Distributed energy resource management for electric vehicles using IEC 61850 and ISO/IEC 15118. In: 2012 IEEE vehicle power and propulsion conference. *VPPC 2012*; 2012. p. 1457–62. https://doi.org/10.1109/VPPC.2012.6422683.
[99] Goteborg Energi, "Effekthandel väst." Accessed: May 5, 2025. [Online]. Available: https://www.goteborgenergi.se/foretag/elnat/effekthandel-vast.
[100] NODES, "FinFlex - NODESmarket." Accessed: May 5, 2025. [Online]. Available: https://nodesmarket.com/finflex/.
[101] NODES, "Euroflex - norway - NODESmarket." Accessed: May 5, 2025. [Online]. Available: https://nodesmarket.com/euroflex/.
[102] Local Markets | OMIE." Accessed: October. 1, 2025. [Online]. Available: https://www.omie.es/en/division-innovacion/mercados-locales.
[103] Electricity North West." Accessed: April. 1, 2025. [Online]. Available: https://www.enwl.co.uk/.
[104] Electron, "ElectronConnect." Accessed: March. 28, 2025. [Online]. Available: https://electron.net/product-electronconnect/.
[105] Piclo, "Piclo flex." Accessed: March. 28, 2025. [Online]. Available: https://www.piclo.energy/flex.
[106] National Grid Electricity Distribution | national grid group." Accessed: April. 1, 2025. [Online]. Available: https://www.nationalgrid.com/electricity-distribution.

[107] National Grid Electricity Distribution, "Market Gateway." Accessed: March. 28, 2025. [Online]. Available: https://marketgateway.nationalgrid.co.uk/.
[108] Northern Powergrid." Accessed: April. 1, 2025. [Online]. Available: https://www.northernpowergrid.com/.
[109] SP Energy Networks." Accessed: April. 1, 2025. [Online]. Available: https://www.spenergynetworks.co.uk/.
[110] Scottish and Southern Electricity Networks - SSEN." Accessed: April. 1, 2025. [Online]. Available: https://www.ssen.co.uk/.
[111] UK Power Networks." Accessed: April. 1, 2025. [Online]. Available: https://www.ukpowernetworks.co.uk/.
[112] Epex Spot, "Local flex market." Accessed: March. 28, 2025. [Online]. Available: https://www.localflex.co.uk/home.
[113] Liander." Accessed: April. 1, 2025. [Online]. Available: https://www.liander.nl/.
[114] Enexis Netbeheer." Accessed: April. 1, 2025. [Online]. Available: https://www.enexis.nl/.
[115] Stedin." Accessed: April. 1, 2025. [Online]. Available: https://www.stedin.net/.
[116] "RENDO Groep o.a. transport gas en elektriciteit." Accessed: April. 1, 2025. [Online]. Available: https://www.rendogroep.nl/.
[117] Coteq Netbeheer." Accessed: April. 1, 2025. [Online]. Available: https://coteqnetbeheer.nl/.
[118] Westland Infra." Accessed: April. 1, 2025. [Online]. Available: https://www.westlandinfra.nl/.
[119] Etpa." Accessed: April. 1, 2025. [Online]. Available: https://www.etpa.nl/en/.
[120] EPEX SPOT." Accessed: April. 1, 2025. [Online]. Available: https://www.epexspot.com/en.
[121] Enedis | Gestionnaire du réseau de distribution d'électricité." Accessed: April. 1, 2025. [Online]. Available: https://www.enedis.fr/.
[122] Enedis, "Flexibilité enedis." Accessed: March. 28, 2025. [Online]. Available: https://flexibilites-enedis.fr/.
[123] Ellevio." Accessed: April. 1, 2025. [Online]. Available: https://www.ellevio.se/.
[124] Vattenfall Eldistribution | Elnät." Accessed: April. 1, 2025. [Online]. Available: https://www.vattenfalleldistribution.se/.
[125] NODESmarket." Accessed: April. 1, 2025. [Online]. Available: https://nodesmarket.com/.
[126] "E-REDES: Distribution of electric energy in portugal." Accessed: April. 1, 2025. [Online]. Available: https://www.e-redes.pt/pt-pt.
[127] Elektro Ljubljana." Accessed: April. 1, 2025. [Online]. Available: https://www.elektro-ljubljana.com/.
[128] E-Distribuzione: distribuzione e misura di energia elettrica | E-Distribuzione." Accessed: April. 7, 2025. [Online]. Available: https://www.e-distribuzione.it/.
[129] "Areti: distribuzione e misura dell'energia elettrica a Roma." Accessed: April. 7, 2025. [Online]. Available: https://www.areti.it/.
[130] Unareti." Accessed: April. 7, 2025. [Online]. Available: https://www.unareti.it/it/home.
[131] Energy Networks Association (ENA),ENA ON - Review of standard flexibility products (Jan 2025).Accessed: April. 1, 2025. [Online]. Available: https://www.energynetworks.org/publications/ena-on-review-of-standard-flexibility-products.
[132] Energy Networks Association (ENA)." Accessed: April. 1, 2025. [Online]. Available: https://www.energynetworks.org/.
[133] Svenska kraftnät." Accessed: April. 1, 2025. [Online]. Available: https://www.svk.se/.
[134] E.ON: It's on us to make new energy work Accessed: April. 1, 2025. [Online]. Available: https://www.eon.com/en.html.
[135] Ellevio | Sthlmflex: Lärdomar och resultat från ett banbrytande flexibilitetsprojekt." Accessed: April. 1, 2025. [Online]. Available: https://www.ellevio.se/nyheter/nyheter/sthlmflex-lardomar-och-resultat-fran-ett-banbrytande-flexibilitetsprojekt/.
[136] Flexibility | Elektro Ljubljana." Accessed: April. 10, 2025. [Online]. Available: https://www.elektro-ljubljana.si/proznost.
[137] Moj Elektro." Accessed: April. 7, 2025. [Online]. Available: https://mojelektro.si/login.
"Arera: Relazione annuale 2024." Accessed: April. 7, 2025. [Online]. Available: https://www.arera.it/chi-siamo/relazione-annuale/relazione-annuale-2024.
[139] GME, "Preliminari MLF." Accessed: April. 7, 2025. [Online]. Available: https://www.mercatoelettrico.org/it-it/Home/Esiti/Elettricita/MLF/MLT-Flex/Esiti/PreliminariMLF.
[140] Lind L, Chaves-Ávila JP, Valarezo O, Sanjab A, Olmos L. Baseline methods for distributed flexibility in power systems considering resource, market, and product characteristics. Util Policy Feb. 2024;86:101688. https://doi.org/10.1016/J.JUP.2023.101688.
[141] Ziras C, Heinrich C, Bindner HW. Why baselines are not suited for local flexibility markets. Renew Sustain Energy Rev Jan. 2021;135:110357. https://doi.org/10.1016/J.RSER.2020.110357.
[142] Sifat MMH, et al. Towards electric digital twin grid: technology and framework review. Energy AI Jan. 2023;11:100213. https://doi.org/10.1016/J.EGYAI.2022.100213.
[143] Barai GR, Krishnan S, Venkatesh B. Smart metering and functionalities of smart meters in smart grid - a review. In: 2015 IEEE electrical power and energy conference: smarter resilient power systems, EPEC 2015; Jan. 2016. p. 138–45. https://doi.org/10.1109/EPEC.2015.7379940.
[144] Strezoski L. Distributed energy resource management systems—Derms: state of the art and how to move forward. Wiley Interdisc Rev Energy Environ Jan. 2023; 12(1):e460. https://doi.org/10.1002/WENE.460.
[145] Insights from running the regulatory sandbox | Ofgem." Accessed: May 13, 2025. [Online]. Available: https://www.ofgem.gov.uk/publications/insights-running-regulatory-sandbox.
Switzerland - GOFLEX." Accessed: May 13, 2025. [Online]. Available: https://goflex-project.eu/Switzerland.html.
[147] GME, "MLF Esiti." Accessed: May 10, 2025. [Online]. Available: https://gme.mercatoelettrico.org/it-it/Home/Esiti/Elettricita/MLF/MLT-Flex/Esiti/PreliminariMLF.
[148] Piclo Max – one marketplace, all markets." Accessed: May 10, 2025. [Online]. Available: https://www.piclo.energy/max.
[149] DSO Entity and ENTSO-E submit Joint network code on demand response." Accessed: Sep. 26, 2025. [Online]. Available: https://www.entsoe.eu/news/2024/05/08/dso-entity-and-entso-e-submit-joint-network-code-on-demand-response/.
[150] European Central Bank, "Pound sterling (GBP)." Accessed: April. 29, 2025. [Online]. Available: https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-gbp.en.html.