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Decoding design characteristics of local flexibility markets for congestion management with a multi-layered taxonomy

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ABSTRACT

Local flexibility markets are becoming increasingly popular smart grid solutions. They connect customers who require flexible electricity supply and demand with local flexibility providers. However, the growing number of diverse solutions has led to a proliferation of concepts, projects, and companies in this market, with this diversity making understanding and comparison difficult. To tackle this challenge, we propose a multi-layered taxonomy of local flexibility market solutions. This focuses on congestion management on the distribution side of this activity; a crucial service for distribution system operators. Our taxonomy utilizes the Smart Grid Architecture Model to describe these markets comprehensively. We employ an iterative taxonomy-building method, refining and evaluating it through insights from ongoing implementations and twenty-eight expert interviews. Moreover, we present a complete instantiation of our taxonomy and offer a discussion with practical recommendations for practitioners in the local flexibility market landscape.

1. Introduction

The evolution to "smart grids" from traditional unidirectional and passive power systems accentuates challenges like real-time power system's balancing and congestion, especially with the proliferation of distributed energy resources (DERs) and sector electrification [1,2]. These complexities, notably at the medium voltage (MV) and low voltage (LV) levels, require System Operators (SOs) traditionally resort to congestion management ancillary services that limit electrical power exchange when line and transformer capacities are reached [3,4].

As these services are often not sufficient, both Distribution System Operators (DSOs) and Transmission System Operators (TSOs) have begun to explore alternatives, such as the use of sources of flexibility [5–7]. SOs can incorporate flexibility sources through non-market-based or market-based solutions [8]. However, certain jurisdictions (such as the European Union (EU)) prefer market-based solutions [9,10]. While various market-based solutions exist, LFMs emerge as a solution for leveraging sources of flexibility and providing services such as congestion management to the SOs [11].

With the burgeoning interest in local flexibility markets (LFMs) for managing congestions and delivering local services, academic literature in this domain has proliferated. Nevertheless, existing research tends to focus in isolation on distinct facets of LFMs—ranging from market designs [11–13] and system architectures [14–16], to technical operations [17–19]. This fragmented approach complicates efforts to compare, select, and regulate such markets. Compounding the challenge is the absence of a homogeneous vocabulary and an integrated perspective, which further exacerbates the complexity of understanding and implementing LFM solutions.

To mitigate this fragmentation, lack of homogeneous vocabulary, and holistic view, we introduce a multi-layered taxonomy of LFMs for congestion management focused on the distribution level. Our taxonomy builds on the Smart Grid Architecture Model (SGAM) as a structuring framework [20], and results from an iterative taxonomy-building process that incorporates insights from currently implemented LFM projects, as well as feedback from twenty-eight expert interviews. It is designed to enhance comprehension of both current and forthcoming LFMs solutions for congestion management, catering to academic, industrial, and regulatory stakeholders. This taxonomy not only refines the vocabulary for mutual understanding and fortifies the SGAM market layer with an intricate classification but also lays the groundwork for subsequent research, such as typologies, ontologies, and archetype designs. Most importantly, it will aid the EU's deployment of LFM solutions by offering standardized definitions and consistent descriptive classification formats that can organize knowledge.

The structure of this manuscript is as follows: Section 2 gives a literature overview of LFMs. It includes the theoretical background, the direction of regulatory change in the EU regarding the development

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of these solutions, and a review of the most prominent EU initiatives with relation to LFM solutions. Section 3 outlines our research approach to create a multi-layered taxonomy for LFM focused on congestion management at the distribution level. Section 4 presents the resulting taxonomy, subdivided according to the SGAM interoperability layer structure. Section 5 provides a complete example taxonomy, based on an existing LFM solution, with three additional examples in the Appendix C. Later, Section 6 discusses and provides recommendations based on our proposed taxonomy's results. Finally, Section 7 concludes the manuscript.

2. Related work

2.1. Local flexibility markets: definitions and design characteristics

2.1.1. Definitions

In essence, LFMs represent a subtype of electricity markets that feature spatial and product concerns. Hence, their "local" and "flexibility" designations. The term "local" refers to certain services and products characterized by a specific geographical location (e.g., congestion management for DSO). Only flexibility providers connected to the given location in the electricity grid can provide the required service [21]. The term "flexibility" refers to the adjustability provided by a range of flexibility sources [22].

Although there are numerous interpretations of LFMs, as collected in Table 1, there is a disagreement on the definitions as not all refer to the concept in the same manner. These definitions, especially Agency for the Cooperation of Energy Regulators (ACER) 's and European Network of Transmission System Operators for Electricity (ENTSO-E)'s incorporate design aspects such as the target group (e.g., DSOs), while in other cases, include trading horizon actions, flexibility grid needs, aggregation, and platform independence. These definitions could lead to confusion and limit the scope of these solutions, especially if collected in regulations or frameworks. To avoid this issue, we provide a broader, more inclusive definition of LFMs as *"information system solutions that enable buyers and sellers to trade flexibility-services to address local needs"*. This definition is not specific to any particular market design, implementation, or service (i.e., congestion management), thus encouraging innovation and allowing for adaptation to various contexts and evolving requirements and designs.

2.1.2. Design characteristics

LFMs represent complex smart grid solutions involving multiple actors, numerous information flows, and multiple components necessary for optimal operation. As interest in these solutions grows, numerous proposals have emerged to address operational challenges, such as congestion management, by providing congestion management services (see Section 2.3). The diverse array of proposed solutions raises critical questions about various market designs, functions, components, and communication modes. These questions are paramount to developers, researchers, regulators, SOs, and users who seek a comprehensive understanding of, comparison between, development of, and analysis of these solutions for future real-world implementation.

Several authors have attempted to address these questions by delving into the design aspects of LFM solutions. Ramos et al. [12] provide a high-level description of the market design characteristics relevant to LFM solutions, exploring dimensions such as temporal, spatial, contractual, and price-clearing aspects. Similarly, Radecke et al. [13] focus on market design elements pertinent to congestion management services, including considerations related to market participants, product and remuneration structures, pricing mechanisms, matching procedures, and clearing processes. Meanwhile, Minniti et al. [16] concentrate on other design elements relevant to all LFM solutions, such as the coordination of market players (i.e., TSO-DSO) and the coexistence of various flexibility services. Valarezo et al. [11] conduct a literature review encompassing different flexibility platforms, including LFM solutions for congestion management. They analyze diverse design characteristics such as pricing strategies, market frequency, bidding processes, settlement mechanisms, market operators' income models, and integration with established electricity markets. Similarly, Färegård et al. [26] delve into specific design characteristics of LFMs that offer congestion management services, covering elements like delivery periods, price settlements, trading platforms, and bid sizes. This detailed examination serves as a foundation for comparing and classifying existing solutions. Additionally, Chondrogiannis et al. [31] provide an in-depth description and comparison of current LFM solutions for congestion management, considering functions like pre-qualification procedures, signal dispatch, validation processes, settlement mechanisms, as well as market design characteristics such as trading mechanisms and flexibility product offerings. In the context of solution design, Troncia et al. [32] introduce a theoretical market framework aimed at conceptualizing and designing electricity markets, applicable to LFM solutions.

Table 1
Local flexibility market literature definitions.

Author	Year	LFM definition
Ramos et al. [12]	2016	*Long- or short-term trading actions for flexibility in a specific geographical location, voltage level, and system operator (DSO and TSO), given by grid conditions or balancing needs, where participants in a relevant market can be aggregated to provide flexibility services*
Olivella-Rosell et al. [18]	2018	*An electricity flexibility trading platform to trade flexibility in geographically limited areas such as neighborhoods, communities, towns, and small cities.*
Radecke et al. [13]	2019	*Mechanism that i) aims to relieve congestion in the distribution grid, ii) works through impacting the dispatch of generation, load and/or storage assets, with iii) voluntary participation, and iv) remuneration that is determined based on participants' bids*
Correa-Florez et al. [23]	2020	*Independent trading space/platform with specific bidding rules*
Ziras et al. [24]	2021	*A market-based solution to trade flexibility locally between flexibility providers and Distribution System Operators (DSOs).*
Dronne et al. [25]	2021	*A local flexibility market is typically used to provide services for the flexibility needs inherent to the Distribution Network Operator (DNO).*
Faregard et al. [26]	2021	*Enablers of explicit DSF, which can be used for several purposes such as managing grid congestions*
Singh et al. [27]	2022	*Trading mechanism for electrical flexibility in geographically constrained regions like communities, neighborhoods, and towns. The LFM provides a competitive trading platform that allows flexibility purchasers, such as DSOs and Balance Responsible Parties (BRPs), to trade flexibility with flexibility sellers, such as aggregators and prosumers.*
ENTSO-E [28]	2022	*Specifically aimed solutions at resolving constraints on the distribution network.*
ACER [29]	2022	*Markets where service providers offer products for local SO services*
Valarezo et al. [30]	2023	*A marketplace that enables buyers and sellers to trade flexibility services to address local needs.*

They focus on design characteristics like market architecture, coordination mechanisms between TSO and DSO, optimization processes, market operation, and grid representation.

In a broader context, Acosta et al. [33] propose a market categorization framework that applies to various smart grid solutions, including LFMs. Within this framework, they emphasize market design aspects such as the degree of competition, agreement structures, clearing mechanisms, price formation, price mechanisms, market product offerings, and the duration of market operations.

Building upon this categorization approach, Teske et al. [34] offer a comprehensive classification of local energy markets, specifically focusing on ancillary services, which congestion management services can fall into. This classification distinguishes between LFMs and local capacity allocation markets, highlighting their distinct characteristics concerning objectives, impact on TSOs and DSO, applications, and the primary challenges they face.

Diving into understanding and categorizing the challenges following a taxonomy-based classification approach, Moller [35] develops a taxonomy. The aim is to understand barriers and potential solutions to flexibility in the district energy-electricity system operated by DSOs. This taxonomy proves valuable for designers and regulators seeking insights into the challenges associated with designing and overseeing, for instance, solutions for DSOs that include flexibility at their core, such as LFM solutions.

Likewise, Mengelkamp et al. [36], adopting a more methodological categorization approach, change the focus to a business-oriented perspective. They derive a taxonomy using a hybrid approach that combines empirical research and conceptual methods. Their taxonomy aims to understand business models' intricacies and defining characteristics within the context of local electricity markets (LEMs) and their relation to LFMs. It draws insights from expert interviews and encompasses aspects related to the value proposition, solution perspectives, partnerships, product offerings, cost and revenue considerations, roles, legal aspects, succession factors, and transactional elements within the solution.

However, these contributions offer only a partial view of the myriad design characteristics of LFMs and their services, particularly regarding congestion management. A comprehensive taxonomy encompassing all design aspects of these smart grid solutions for congestion management could serve as the foundation for detailed and harmonized descriptions. Such a comprehensive taxonomy would greatly enhance our ability to compare and analyze LFM solutions, thereby significantly advancing our understanding of these complex systems. Importantly, this taxonomy must encompass many perspectives beyond the purely business aspect, as LFM represents complex smart grid solutions.

2.2. European regulation push towards local flexibility markets

LFMs have become a central policy focus for the EU, catalyzed by the European Commission (EC)'s strategic endeavors to revolutionize the power landscape. Driven by the trinity of decarbonization, decentralization, and digitalization [37], the ambition is a robust, sustainable energy infrastructure, with LFMs at its helm, aiding SOs in efficient grid management.

The genesis of this regulatory trajectory traces back to the third energy package of 2009, which evolved in 2016 with the fourth energy package or Clean Energy Package (CEP) proposal, outlining a framework for DSOs to harness flexibility. Subsequent policy inflections in 2019 further supported LFMs via the European Green Deal [38], with 2020 heralding the Energy System Integration Plan [39] and the EU Digital Strategy [40], both underscoring the salience of platforms like digital LFMs solutions.

In 2021, the scene was set for more radical shifts. Directives on Renewable Energy [41] and Energy Efficiency [42] accentuated non-discriminatory market participation, congestion management, and demand-side flexibility. These culminated in the 2021 'Fit For 55' package, setting an ambitious renewable energy resource (RES) target of 40% by 2030 [43], implying deeper grid complexities at LV and MV levels and a pressing call for LFM solutions for smooth RES assimilation.

Additionally, the EU's REPower initiative [44] sought to expedite the energy shift, seeking demand moderation, fuel source diversification, and higher RES integration. This momentum carried into 2022 when the EU Commission encouraged ACER for a comprehensive demand response framework, emphasizing SOs's pivotal role in local market operations, as it clearly states SO can use LFM to procure flexibility [29].

In sum, the EU's evolving policy landscape profoundly recalibrates the regulatory climate, reshaping grid and market paradigms. As challenges to the legacy power model mount, they concurrently create a push for innovative solutions like LFMs to navigate and thrive amid these changes [31].

2.3. Overview of local flexibility markets for system operators in Europe

LFMs have generated substantial attention as a way to achieve the integration of many regulatory changes while being a cost-effective complement for SOs. Hence, many EU projects have focused on the research and development of LFM solutions. Table 2 presents a comprehensive overview of the most pertinent European initiatives that currently feature LFM solutions for the procurement of SO services via platforms. Many of these initiatives have emerged from the European H2020 research program, including projects such as CoordiNet [45,46], EUniversal [47,48], EU-SysFlex [49,50], InterFlex [51,52], and OneNet [53,54]. These projects involve multiple partners from different European countries, as outlined in Table 2. Furthermore, Germany and Denmark have introduced their own national initiatives, namely Enera [55] and Ecogrid 2.0 [56] – to facilitate the procurement of flexibility services. Additionally, the Cornwall Local Energy Market [57] in the UK – which was led by Centrica and partially funded by the European Regional Development Fund – developed a market-based to DSO and TSO flexibility procurement arrangements.

Other LFM solutions have been developed independently by SOs. For instance, Flexible Power [58] is a collaborative effort of four UK electricity distribution network operators (DNOs): National Grid Electricity Distribution, Northern Powergrid, Scottish and Southern Electricity Networks, and SP Energy Networks. Similarly, Enedis – the main DSO in France – created and operates a local flexibility platform to procure congestion management services [59]. Moreover, GOPACS [60], owned and operated by the Dutch–German TSO TenneT and four DSOs (Stedin, Liander, Enexis Groep, and Westland), serves as an intermediary platform supporting the coordinated market-based procurement of congestion management services. Another relevant flexibility platform is being developed by OMIE, the nominated electricity market operator (NEMO) for the Iberian Peninsula (Spain and Portugal). This initiative builds upon the work carried out in the OneNet [53], DRES2MArket [61] and IREMEL [62] projects.

On the other hand, there are commercial solutions that offer marketplaces for the procurement of flexibility services. For instance, Piclo [63] operates in the UK and has expanded its operations to Ireland, Lithuania, Portugal, and the United States. Similarly, NODES [64] is an independent marketplace that functions as a market operator as part of various projects such as Mitnetz [65], NorFlex [66], Smart Senja [67], SthlmFlex [68], among others. Most of the analyzed initiatives are either fully operational or completed, with the exception of EUniversal, OneNet, and the OMIE LFM, which were at the implementation stage at the time this research was conducted.

Table 2
Overview of local flexibility market platforms implemented in Europe since 2016.

Service objective	Market type	Use Cases	Status	Countries	# UCs
Congestion Management	Flexibility market for DSO	CoordiNet: BUC-ES-1b, BUC-SE-1a/1b	2019–2022	ES-SE	25
		EUniversal: BUC-PT1	2020–2023	PT	
		Flexible Power: National Grid Electricity Distribution, SP Energy Networks, Northern Power Grid, Scottish and Southern Electricity Networks	In operation	UK	
		InterFlex: FR-UC3, NL demo	2017–2019	FR-NL	
		NODES: Mitnetz	2018–2021	DE	
		NODES: Smart Senja	In operation	DE-NO	
		OneNet: WECL-ES-01/02, EACL-HU-02, EACL-SL-01	2020–2023	ES-HU-SL	
		Piclo: UK Power Networks, Electricity Northwest	In operation	UK	
		OMIE: IREMEL and DRES2Market	In development	ES	
		Enedis: local flexibility platform	In operation	FR	
	Flexibility market for DSO and TSO	CoordiNet: BUC-GR-2a/2b	2019–2022	GR	
		Cornwall LEM	2016–2020	UK	
		Enera: Northwest of Germany use case	2017–2020	DE	
		GOPACS	In operation	NL	
Voltage Control	Flexibility market for DSO	EUniversal: BUC-PT2	2020–2023	PT	6
		EU-SysFlex: FI demo	2017–2021	FI	
		OneNet: EACL-HU-01, EACL-SL-02	2020–2023	HU-SL	
	Flexibility market for DSO and TSO	CoordiNet: BUC-GR-1a/1b	2019–2022	GR	
Congestion Management and Voltage Control	Flexibility market for DSO	EUniversal: BUC-DE-AP/RP, BUC-PL-AP/RP, BUC-PT3/4	2020–2023	DE-PL-PT	11
		Ecogrid 2.0: BC3 Flexibility services at DSO level	2016–2019	DK	
		OneNet: EACL-CZ-01/02/03	2020–2023	CZ	
	Flexibility market for DSO and TSO	EU-SysFlex: Portuguese demo PT-FxH-RP	2017–2020	PT	
Congestion Management Balancing	Flexibility market for DSO and TSO	EU-SysFlex: Italian demo IT-AP	2017–2021	IT	3
		NODES: NorFlex	2019–2022	NO	
		NODES: SthlmFlex	In operation	SE	
Congestion Management, Voltage Control Balancing	Flexibility market for DSO and TSO	OneNet: SOCL-CY-01/02, EACL-PL-01/02/03/04	2020–2023	CY-PL	6
Islanding	Flexibility market for DSO	CoordiNet: BUC-ES-4	2019–2022	ES	1

2.3.1. *Observations*

Two types of market designs were identified in these projects: Flexibility Markets for DSOs and Flexibility Markets for DSOs and TSOs. The former represents a market-based mechanism allowing DSOs to procure system services from flexibility service providers (FSPs) to address local needs, with DSOs maintaining exclusive access to DERs. In the latter, flexibility markets for DSOs and TSOs, flexibility is distributed between system operators through market-based coordination, such as bid forwarding, value stacking or priority-in-bid-selection. In this instance, LFMs at distribution level typically function as the initial stage of the process. It is important to highlight that flexibility markets which are used exclusively for TSOs are excluded from the analysis. This is because this paper focuses on LFMs at the distribution level.

Furthermore, we identified and examined fifty-two use cases (UCs), all of which used LFM platforms as collected in Table 2. We categorized them into six groups based on their service objectives.

The first group comprises UCs for testing congestion management solutions. In nineteen of these UCs, the DSO aims to procure flexibility to resolve or mitigate physical congestions (specially, the overloading of lines and/or transformers) using active power products. In the remaining UCs, the TSOs and DSOs procure flexibility to address congestion issues through TSO - DSO coordination schemes [21]. The second group comprises six UCs which provide voltage control services. These UCs share similarities with congestion management UCs. However, their focus diverges slightly as their solutions rectify voltage violations using reactive power or a combination of active and reactive power. The following groups propose market-based solutions that combine congestion management services with voltage control and/or balancing services. For instance, projects such as EUniversal, OneNet, Ecogrid 2.0, and EU-SysFlex have implemented UCs that focused on LFMs for the joint procurement of congestion management and voltage control services. In the market-clearing of these solutions, any active and/or reactive power flexibility bids from providers could solve lines/transformers overloading, bus voltage violation, or both. The last group includes the CoordiNet UC-ES-4, which centers on islanding service (i.e., a type of microgrid operation).

Among the reviewed UCs, congestion management service emerges as the most prevalent service in local flexibility markets. Consequently, the proposed taxonomy concentrates primarily on this service alone and uses these UCs as a foundation to develop it.

3. Research approach

This research paper proposes a multi-layered taxonomy for LFMs focusing on congestion management at the distribution level. We limit our taxonomy to the area of congestion management, as it is the main service for DSOs and where the main pilot projects and companies are directing their efforts (see Section 2.3). We propose our definition of LFMs in Section 2.1. We refer to congestion management services as mitigating the restriction of electrical power exchange through the electrical grid, with this largely dependent on the capacity of transmission/distribution lines and transformers. Line or transformer capacity can be restricted by physical constraints, such as thermal loading or hosting capacity, or by nonphysical factors, such as contract power limitation. This is a particular concern for smaller DSOs when contracting power capacity from larger DSOs.

3.1. Smart grid architecture model framework

The SGAM is a fundamental part of our taxonomy-building approach because LFMs are smart grid solutions. The SGAM can provide a harmonized description of smart grid solutions [20]. It requires a business-case or other use-case as a context from which to provide a description. The SGAM emerges from the M/490 EU mandate, which asks the Smart Grid Coordination Group (CEN, CENELEC, and ETSI members) to develop a framework to enable European standardization in the field of smart grids, while maintaining transverse consistency and promoting continuous innovation [20].

The SGAM framework is widely employed within the EU to provide comprehensive descriptions of smart grid solutions. It is used by various initiatives, such as research projects and their scientific publications [46,51,53,69], as well as task forces in Europe, including the European Smart Grids Task Force Expert Group 1 [70] and the Data Management Working Group [71]. These entities highly recommend using the SGAM to achieve a holistic and harmonized depiction of solutions.

The SGAM divides the description of a smart grid solution into five interoperability layers: (1) Business, (2) Function, (3) Information, (4) Communication, and (5) Component, as we depict in Fig. 1 [20].

The business interoperability layer provides an overview of the economic and regulatory structures of the solution. The function interoperability layer describes the services and tools relationships from an architectural viewpoint. The information interoperability layer describes the exchange of information and its underlying canonical data models. The communication interoperability layer describes the protocols and mechanisms for information exchange between components. Finally, the component layer provides an overview of the power system devices and information and communication technology (ICT) equipment used to operate the solution.

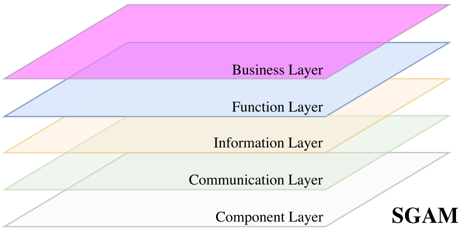

Fig. 1. Interoperability layers of the Smart Grid Architecture Model based on [20].

As a result, the SGAM offers a harmonized power system framework for the description of smart grid solutions. Consequently, we use it to structure the descriptions in our taxonomy. For each interoperability layer, we create a separate taxonomy. Using a detailed SGAM – such as the one in [72], which covers all five interoperability layers – we can provide a comprehensive, integrated, and harmonized description of our LFM solution. However, even a partially described solution that covers one or more interoperability layers can still help to identify objects. We aim not to map our taxonomy onto the SGAM, but to use it as a boundary to define and describe each specific interoperability layer and, as a result, our LFM solution.

3.2. Taxonomy building method

Traditionally, taxonomies are means of classification using empirical observations of identified objects [73]. However, given the rapid evolution of LFMs and regulations, relying solely on empirical data may result in an outdated taxonomy. Therefore, we incorporated conceptual information to enhance and strengthen our taxonomy. We selected the extended taxonomy design process (ETDP) method proposed by Kundisch et al. [74] as it builds from Nickerson et al. [75] and extends the evaluation step (see Appendix A–Fig. A.1 for convenience).

The process of building a taxonomy involves several steps. Researchers start by specifying the observed phenomena (i.e., the matter of research), the target groups, and the intention of the research. Next, they determine the meta-characteristics of the taxonomy, which provide the essence of the classification. Then, researchers need to determine their ending conditions and evaluation goals. Succeeding steps then focus on the main building blocks of the taxonomy through a step-oriented method that involves empirical (E-2-C) and/or conceptual (C-2-E) iterations to drive the dimensions and characteristics of the taxonomy. In our case, we used a mixed approach that combines both iterations. The taxonomy is defined by a set of dimensions, each consisting of mutually exclusive characteristics. Dimensions can be considered variables, while characteristics can be considered possible values of these variables [75]. Taxonomies can be multi-layered to increase comprehension and readability [74]. In our case, we use the term “category” instead of “layer” to avoid naming convention problems with the SGAM interoperability layers. After each iteration, researchers revise the taxonomy and check their ending conditions. If they meet their ending conditions, they continue by configuring and performing the evaluation. Once the researchers meet their evaluation goals, they can consider that they have finalized the taxonomy and can then report it.

To develop our taxonomy, we focused on observing the phenomenon of local flexibility market platforms and identified three user target groups: (1) Academic, (2) Industrial, and (3) Regulatory. The taxonomy serves as a foundation from which to describe, understand, classify, and analyze LFM platforms in a harmonized fashion. Therefore, the established meta-characteristic is: *“Design characteristics of local flexibility market platforms focused on congestion management at distribution level in the EU”*.

We assumed four objective ending conditions. Objective conditions provide a clear and straightforward means for researchers to check their stopping conditions. The first condition is to cover a representative sample of objects, in our case, commercial solutions and EU projects. To do so, we analyzed commercial and development solutions available such as Piclo [63], NODES [64], OMIE [76], GOPACS [60],[1] which are

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[1] It is not considered a local flexibility market per-se, but we considered it nonetheless, as it can help with the evaluation process and is an experiment for the usefulness of the taxonomy.

the leading commercial solutions. We also analyzed the details of the main EU projects targeting LFM selected from our literature analysis (see Section 2.3). The second condition is to stop iterating if we do not perform any merge or split operations in the previous iteration (see [74]). The third condition is that every dimension and characteristic must be unique for each interoperability layer. The fourth condition is that the combination of characteristics is unique and not repeated. In a similar fashion, as authors from the same discipline [36,77] or other disciplines have done [78,79], we incorporated an additional mutually exclusive marker as a new column in our taxonomy. This mutually exclusive marker delineates whether characteristics are unique or if multiple characteristics can apply within a single dimension. Moreover, the mutually exclusive clause facilitates a reduction in the number of characteristics, as it prevents the need to specify their combinations.

We assumed five subjective ending conditions. Subjective ending conditions are more complex to check. This is because they depend, to a large extent, on each researcher's point of view. First, the taxonomy must be concise. Consequently, we aimed to limit the number of dimensions and characteristics in each dimension to locate and capture abstraction and conciseness. Second, the taxonomy must be sufficiently robust to provide differentiation between objects based on the dimensions and characteristics of the taxonomy. Third, it has to be comprehensive to enable a (random) sample of objects within the domain to be classified. Fourth, it has to be extendable so that new dimensions or characteristics can be added easily. Fifth, it has to be largely self-explanatory; in other words, the naming convention has to be intuitive.

3.3. Iterations

We required a total of sixteen iterations as collected in Table 3. The first iteration, $I = 1$, was a C-2-E iteration focused on reviewing existing literature on topics related to our taxonomy. We used search strings that included *congestion management, local flexibility markets, local energy markets, taxonomy, and smart grid architecture*. We conducted our review using online libraries such as *IEEE Xplore* [80], *Science Direct* [81], and *Semantic Scholar* [82]. We also utilized our professional and academic knowledge, as well as the projects we reviewed (see Section 2.3). The initial outcome of $I = 1$ was the initial version, $V1$, which we further enhanced through subsequent revisions.

Subsequent versions of the taxonomy resulted from E-2-C approach iterations. In our E-2-C iterations, we used the latest version of the taxonomy and conducted interviews to enhance the taxonomy. In total, we interviewed twenty-eight experts from different backgrounds. We selected our pool of candidates based on their experience in the context of LFMs and, if possible, knowledge in the SGAM domain. We provide details from our expert interviews in Table 4. We employed a semi-structured interview format and used the drama model as our guiding framework [83]. We conducted the interviews in Spanish and English. Before initiating each interview, we obtained consent from our experts to record and transcribe the conversation. We could record all the interviews and analyze the transcription to complete, modify, or adapt them. In each interview, we introduced our motivations and objectives, explained our research approach, provided an overview of our taxonomy per SGAM interoperability layer, discussed the taxonomy, and concluded by asking for their feedback. We collected their feedback on the taxonomy and literature recommendations, allowing us to build upon refined versions, as well as cross-checking comments from all interviewees.

After iteration $I = 4$, we introduced the *category* "layer" in our taxonomy to provide a better context for the dimensions and their characteristics, following interviewee recommendations and analyzing similar approaches in the literature [77–79].

Subsequent iterations, $I = 12$ and $I = 14$ incorporated cross-national use cases (Netherlands (NL), Spain (ES), and the UK), with iteration $I = 12$ emphasizing interview-based insights and iteration $I = 14$ scrutinizing extant documentation. The shift was because interviewees from $I = 13$ recommended instantiating the taxonomy to (1) check its completeness, (2) determine its ability to distinguish real-world objects, and (3) analyze any potential constraints when populating it. After two more iterations, we met all the ending conditions considered and performed the evaluation.

3.4. Evaluation

We evaluated our taxonomy in a two-stage process. The first stage involved mid-term feedback from interviewees at the end of the interviews and the instantiation of the taxonomy in iterations $I = 12$ and $I = 14$ to identify areas for improvement and refinement of the taxonomy, ensuring its practical relevance and alignment with real-world expectations.

The second stage occurred post-completion, after iteration $I = 16$. We used a qualitative question-based method, drawing from the guidelines of Kundisch et al. [74], March et al. [84], and Prat et al. [85], to assess various dimensions including completeness, ease of use, and robustness. We developed a set of open-ended questions to evaluate the *completeness*, *ease of use*, *simplicity*, *understandability*, *fidelity with the real world*, *consistency*, *level of detail*, and *robustness* of our taxonomy. At the same time, we invited all the interviewees from the taxonomy-building process by email (Bcc) to share their feedback and answer

Table 3
Overview of iterations carried out to complete the taxonomy.

Overview				Categories	Dimension[a]					Characteristics[a]				
Iteration	Version	Type	Data (i = interviewee)	Number	B	F	I	C	Comp	B	F	I	C	Comp
1	V1	C-2-E	Own, literature and project documentation	–	19	3	2	6	9	63	15	7	18	23
2	V2	E-2-C	V1 + i_1	–	16	2	2	6	8	53	13	7	20	22
3	V3	E-2-C	V2 + i_2	–	17	2	2	6	8	57	14	7	20	21
4	V4	E-2-C	V3 + i_3	18	17	7	3	6	7	44	20	11	16	18
5	V5	E-2-C	V4 + i_4	18	17	7	3	6	7	44	20	11	15	18
6	V6	E-2-C	V5 + i_5 + i_6 + i_7	21	23	7	3	6	7	53	20	11	16	18
7	V7	E-2-C	V6 + i_8	21	23	7	3	6	7	53	20	11	15	18
8	V8	E-2-C	V7 + i_9	23	20	7	3	8	7	50	20	11	16	19
9	V9	E-2-C	V8 + i_{10} + i_{11}	23	21	7	3	8	7	54	20	11	16	19
10	V10	E-2-C	V9 + i_{12} + i_{13} + i_{14} + i_{15} + i_{16}	23	21	7	3	8	7	57	20	11	16	19
11	V11	E-2-C	V10 + i_{17} + i_{18} + i_{19}	24	21	7	3	8	7	59	20	11	16	19
12	V12	E-2-C	V11 + i_{20} + i_{21} + UC (NL)	24	21	7	3	8	7	53	21	11	16	18
13	V13	E-2-C	V12 + i_{22} + i_{23} + i_{24} + i_{25} + i_{26}	23	21	6	3	8	6	52	18	11	16	16
14	V14	C-2-E	V13 + UC (ES, UK)	25	24	6	3	8	6	62	18	11	16	16
15	V15	E-2-C	V14 + i_{27}	23	22	7	3	8	6	52	21	11	16	16
16	V16	E-2-C	V15 + i_{28}	24	21	7	3	8	6	50	20	11	16	16

[a] B = Business, F = Function, I = Information, C = Communication, Comp = Component.

Table 4
Interview details.

ID	Country of activity	Sector	Position	Topic expertise	SGAM expertise[a]	Duration (min)	Interview setup	
1	Spain	University	Researcher	LFM and SGAM	B, F	103	Physical	Individual
2	Spain	University	Research assistant	LFM and SGAM	B	102	Physical	Individual
3	Spain	University	Research professor	LFM	B	82	Physical	Individual
4	Spain	University	Professor	LFM	B	76	Physical	Individual
5	Spain	University	Research assistant	LFM and SGAM	I, C, Comp	100	Physical	Group
6	Spain	University	Professor	SGAM	I, C, Comp	100	Physical	Group
7	Spain	University	Assistant Professor	LFM and SGAM	I, C, Comp	100	Physical	Group
8	Spain	Industry	DSO role	LFM and SGAM	B, Comp	102	Online	Individual
9	The Netherlands	Industry	Senior consultant	LFM	B	100	Online	Individual
10	Austria	Research	Head of research unit	LFM and SGAM	All	72	Online	Individual
11	Germany	Industry	Senior project manager	LFM	B	86	Online	Individual
12	Austria	Research	Head of research unit	LFM and SGAM	F, I, C, Comp	68	Physical	Individual
13	Austria	Research	Researcher	LFM and SGAM	F, I, C, Comp	71	Online	Individual
14	N-W & central Europe	Industry	Manager business development	LFM	B	83	Online	Individual
15	Spain	Industry	Senior developer	LFM	B	93	Online	Group
16	Spain	Industry	Senior developer	LFM	B	93	Online	Group
17	Austria	Research	Researcher	LFM and SGAM	F, I, C, Comp	74	Physical	Group
18	Austria	Research	Researcher	LFM and SGAM	All	74	Physical	Group
19	Portugal	Research	Head of research unit	LFM and SGAM	All	54	Online	Individual
20	The Netherlands	Industry	Project manager (DSO)	LFM and SGAM	B	80	Physical	Group
21	The Netherlands	Industry	Product owner flexibility systems (DSO)	LFM and SGAM	B	80	Physical	Group
22	Belgium	Policy	Policy advisor	LFM	B	76	Online	Group
23	Belgium	Policy	Management, Lead & Advisor	LFM	B	76	Online	Group
24	Norway	Policy	Senior Engineer	LFM	B	86	Online	Individual
25	United Kingdom	Industry	Economic Consultant	LFM	B	84	Online	Individual
26	Greece	Policy	Policy freelancer	LFM and SGAM	All	146	Online	Individual
27	Belgium	Policy	Head of research	LFM and SGAM	B	66	Online	Individual
28	Belgium/EU	Industry	Flexibility Manager	LFM and SGAM	B	89	Online	Individual

[a] B = Business, F = Function, I = Information, C = Communication, Comp = Component.

our questions. Table B.1 collects these questions in Appendix B. All twenty-eight experts interviewed responded positively, although three also shared minor comments.

On the one hand, these experts acknowledged that the taxonomy effectively bridges the gap between diverse terminologies and facilitates accurate, holistic understanding. They also appreciated its completeness, which covers the entire perspective of these solutions and provides a solid foundation. Additionally, they noted the balanced abstraction level, which helps avoid the taxonomy becoming quickly outdated.

On the other hand, the experts expressed the following minor concerns. First, they recognized that the taxonomy, although complete, well-structured, and detailed, requires a certain level of expertise to understand. This is because it encompasses intricate elements that may necessitate prior knowledge or supplementary information for non-experts. Second, periodic updates to the taxonomy may be necessary, particularly in response to regulatory changes. However, they also acknowledged that such changes would require minimal work due to the logical structure of the taxonomy and the followed method. Thus, the expressed concern in reality aligns with the inherent nature of taxonomies, which, as suggested by Nickerson et al. [75], should be extensible, dynamic, and not merely static to adapt to changes. Finally, some respondents noted that they could provide a more detailed answer regarding the ease of use once they used the multi-layer taxonomy, although it seems straightforward at first glance.

As final remark, during a presentation at a doctoral workshop [86], we received positive feedback on the elegance of the taxonomy. This was principally due to the way it incorporates the SGAM's structure, thus contributing to a well-organized taxonomy.

4. Taxonomy

In the following section, we introduce our taxonomy, organized into five SGAM interoperability layers detailed in subsequent subsections. In each taxonomy, the extra column indicates whether characteristics are mutually exclusive (ME)—"yes" for unique characteristics and "no" for combinable ones.

4.1. Business interoperability layer

In Table 5, we present our proposed taxonomy for the business interoperability layer, featuring nine categories, 21 dimensions, and 50 characteristics. The nomenclature aligns with the latest frameworks from ACER [29], universal smart energy framework (USEF) [87], and ENTSO-E [88].

The first category in our taxonomy focuses on congestion management needs (CM needs), which are classified into planned and unplanned origins. Planned needs are predictable and stem from network expansion plans, allowing the SO to prepare accordingly. Unplanned needs arise from sudden or post-fault scenarios, making it uncertain if corrective measures will be needed, as seen in cases from Spain [76] and the UK [89].

The second category in our taxonomy identifies the primary players in an LFM: flexibility buyers, FSPs, and the market operator. Our taxonomy focuses on DSOs, or a combination of DSOs and TSOs, as the main flexibility buyers for congestion management at the distribution level. We have identified two types of market designs for this in Section 2.3. In the first design, one or multiple DSOs can act as buyers in an LFM. In the second design, both DSOs and TSOs can purchase flexibility through market-based coordination, with an LFM serving as the initial stage. We identified two key types of FSPs: aggregators and individual providers. Aggregators can be further classified into traditional and independent models according to [90,91], but this taxonomy does not cover it.

The role of market operators in LFM is a subject of debate as remarked in [92,93]. While some DSOs may operate the market, upcoming EU regulations and frameworks [29] suggest multiple operator options, including independent entities like Piclo or regulated ones as NEMOs. LFM operators have similar responsibilities to traditional market operators but may take on additional tasks when an SO assumes this role, such as resource prequalification or flexibility activation [94].

The third category, market scope, contains three dimensions: negotiation time frame, grid level location of flexibility needs, and location organization of offers. The negotiation time frame concerns the "gate" opening and "gate" closure for customers to participate in flexibility

Table 5
Taxonomy based on the business interoperability layer for congestion management service.

Category	Dimension	Characteristic				ME
CM need	Origin	Planned	Unplanned			Yes
Participants	Flexibility buyer	DSO/s	DSO + TSO			Yes
	Flexibility service provider	Aggregator/s	Individual provider/s			Yes
	Market operator	System operator/s	Third-party commercial	Third-party regulated		No
Market scope	Negotiation time frame	Real-time	Short-term	Mid-term	Long-term	Yes
	Flexibility need – grid level	DSO HV	DSO MV	DSO LV		No
	Offer organization	Congestion point/s	Congestion zone/s			No
Market access	Prerequisites	Technical	Market			No
Product	Attributes(Parameters)	Not standardized	Standardized for UC/BC only	Standardized at country level		No
	Transactional object	Energy (Activation)	Capacity (Availability)			No
	Power	Active Power	Reactive Power			No
	Direction	Upwards	Downwards			Yes
Clearing	Matching	Continuous market	Call market			Yes
	Demand/Supply formation	One side Market	Two side Market			Yes
	Grid constraint representation	Bid limitation	Partial grid data	Comprehensive grid data		Yes
	Pricing rule	Pay-as-clear	Pay-as-bid			Yes
Metering verification	Flexibility unit metering	Portfolio	Asset			No
	Baseline method	Historical data	Real-time data	Alternative data		No
Integration	External coordination	Implements MO/s coordination	Does not implement coordination			Yes
	Existing market interaction	Defined	Undefined			Yes
Economic	Fees	Fixed	Variable			No

markets with their bids (flexibility offers). Customers can participate in flexibility markets, ranging from real-time to long-term. Real-time encompasses same-day market negotiations, short-term refers to hours to a day, mid-term includes weeks to months, and long-term extends over years. The grid level location is crucial for distribution networks as it dictates the effectiveness of congestion solutions. Here, we adhere to the EN 50160 and E.DSO (European DSOs association) guidelines [95, 96] and consider high voltage (HV), MV, and LV levels excluding Extra-HV because of our distribution-level focus. The offer location organization dimension contains two main characteristics: congestion points and congestion zones, which may dynamically change over time according to real projects [97]. These dimensions incorporate insights from various studies and guidelines, such as EN 50160, E.DSO reports, and practices in countries like Spain, the Netherlands, and the UK (see Section 4).

The fourth category, market access, outlines the prerequisites that FSP must meet to enter the market. These prerequisites can be technical (such as prequalification of assets and communication with assets) or market-specific. Market-specific prerequisites may involve providing company information, collateral for participation, or declaring responsibility for balancing.

The fifth category refers to the product. Our research found that companies and research projects may use various attributes to describe a congestion management product. For example, the OneNet project [98] introduces a framework that categorizes product attributes in two different levels: technical attributes (e.g., traded commodity, location of delivery, level of availability, ramping period, required mode of activation, etc.); and bid related attributes (e.g., divisibility, granularity, availability and activation prices, aggregation allowed, etc.). Similarly, the Open Networks project in the UK [99], outlines specific attributes for active power products, including minimum flexible capacity, maximum ramping period, minimum activation capability, availability agreement period, among others, mixing the technical and bid related attributes. Such a classification into technical and bid-related (similar to OneNet project) provides a simple structure but lacks depth. In order to provide depth into the taxonomy, we incorporate several dimensions to provide insights at a technical level and later at a market level. Thus, from a technical perspective in the product, to provide a concise set of parameters – rather than an extensive and dynamic list that may change due to upcoming regulations in the EU (e.g., ACER's demand response framework guidelines [29]) – we focused on how standard or common these characteristics are in the operational context. We segmented them into three levels of standardization: non-standardized, standardized for the use case/business case, and standardized at the country level. The non-standardized characteristic offer customization at the cost of complexity and are specific to individual contracts or flexibility needs. Standardized for the use case/business, like those in NODES, balance customization and efficiency and are specific to congestion management as they can be replicated across countries since they are use case dependent. Lastly, *standardized at the country level* aims to provide a cohesive framework for all market participants within a country, as seen, for example, in the UK. Future guidelines from ACER may encourage but not enforce this level of standardization. The transactional object dimension describes the traded commodity: energy (activation or utilization as known in the UK) or capacity (availability). It is essential to emphasize that our taxonomy acknowledges the possibility of combining these characteristics to create specific and unique variations. Additionally, depending on the design and the product at hand, capacity products may introduce further nuances, such as traditional capacity or capacity limitation (e.g., dispatch limitation), as highlighted in the framework guidelines [29] or in proposed designs as in [100]. Nevertheless, from an abstract perspective, these still revolve around capacity. The power dimension refers to the product's nature, which can be active or reactive power. While most congestion markets emphasize active power, recent EU projects like Coordinet [46] and EUniversal [47] explore the use of reactive power. The direction dimension distinguishes between upwards (increasing generation or reducing consumption) and downwards (decreasing generation or increasing consumption). Even though limiting power direction could constrain market liquidity, it can also offer clarity and simplification for both flexibility buyers and FSPs, thus influencing the LFM's overall effectiveness.

The sixth category refers to market clearing, which is crucial in any market-based procurement system. It outlines the operational and management aspects of the market. The clearing matching dimension, in its abstraction, can be either a continuous market (e.g., intraday continuous), or a call market approach for procuring services. The call market – which includes tenders, bilateral contracts, or various types of auctions [17,101,102] – has been the subject of much discussion during interviews. The key distinction is that while the continuous market clears frequently, the call market has an opening and closure period for FSPs to submit their offers. The demand/supply formation dimension in market clearing refers to either one-side or two-side markets. In one-sided markets, the focus is mainly on meeting the buyer's needs, often selecting bids based on criteria like the lowest price. In contrast, two-sided markets balance both buyer and seller offers, determining the market-clearing point where demand and supply intersect. The grid constraint representation dimension distinguishes between bid limitation, partial grid data, and comprehensive grid data. Bid limitation relies solely on bid information for market clearing. Partial and comprehensive grid data involve varying degrees of network information to address location-based congestion needs as indicated in [54]. The pricing rule dimension identifies if the market operates under pay-as-clear or pay-as-bid mechanisms [103].

During the taxonomy development process, two additional potential dimensions emerged: price capping and the organization responsible for clearing. The issue of price capping was considered outside the scope of the business layer. It can be included in the information taxonomy interoperability layer as market information (see Section 4.3). As a side note, DSOs might use budgets instead of price caps for purchasing flexibility. The second dimension, which pertains to the entity in charge of clearing, was found to overlap with the functional taxonomy. As such, we restricted it to the functional layer, focusing on the managerial responsibilities associated with each function (see Section 4.2).

The seventh category focuses on metering verification. It significantly influences the settlement process and, thus, the service payment. We focus on two key dimensions: flexibility unit metering and baseline methods. Flexibility unit metering can be portfolio-based or centered on individual assets, using either main metering or specialized submetering. Baseline methods are categorized into three main types: based on historical data (where any previous data helps infer the baseline); real-time data (as monitoring or nowcasting (prediction in a very short time ahead) provides); or any alternative data (such as schedules or nominations). These examples are non-exhaustive as pointed out in [24,45,104].

The eighth category focuses on market integration. We split it into two main dimensions: external coordination and existing market interaction. External coordination pertains to whether the LFM interfaces with other network operators (DSO-DSO, TSO-DSO) or market operators or remains isolated. Existing market interaction investigates the relationship between the LFM and existing markets like day-ahead or intraday. For example, OMIE in Spain plans to leverage day-ahead market data in their developing LFM. The OneNet project also explores how LFMs interact using primarily bid forwarding with established energy and ancillary markets [54].

We dedicate the last category in our business taxonomy to the economic aspect, which considers the LFM fees that can be fixed or variable. LFM platform solutions might include many different fees and might only be equal to some participants. For example, fixed fees could refer to the cost of the LFM solution in terms of infrastructure, with participants facing a fixed fee to use it paid once or by subscription or even mutualized by all end-customers. Variable fees may refer to trading fees based on total volume or penalties or price reductions FSP might face upon non-delivery of their product.

4.2. Function interoperability layer

Table 6 collects the taxonomy for the function interoperability layer consisting of three categories, seven dimensions, and twenty characteristics. It aims to classify the functions required to perform in an LFM. The number of functions to classify may vary depending on the description and complexity of the LFM use case. We recommend the following steps to use the proposed function interoperability layer taxonomy effectively:

1. Identify all functions present in the LFM solution by selecting the best representative characteristics of the Scope dimension.
2. For each identified function and its scope, describe the other two categories (Management and Computation) by selecting one characteristic per dimension.

Aligned with studies by ENTSO-E [28] and Office of Gas and Electricity Markets (OFGEM) [105], our taxonomy for the function interoperability layer of LFM includes:

1. Assessment Functions: Cover activities such as monitoring and forecasting for flexibility management.
2. Trading Functions: Focus primarily on bid selection and market processes.
3. Communication Functions: Facilitate coordination and information sharing, exemplified in H2020 projects like InteGrid [69] and EUniversal [106].
4. Dispatch Functions: Relay selected offers to FSPs for subsequent asset operation.
5. Activation Functions: Initiate the operation of flexibility assets based on specific parameters.
6. Validation and Settlement Functions: Interlinked functions that verify and finalize contracts and deliveries, also triggering payment processes.

The differentiation between dispatch and activation emerged from the interviews and research [31]. While they might appear synonymous or often treated together in some contexts, they serve distinct roles in many scenarios. For example, a DSO may issue a dispatch order well in advance, specifying the flexibility requirements. However, the actual activation, which puts these requirements into effect, is typically carried out by the FSP at a designated later time. This separation underscores the nuanced roles these functions can play in operating an LFM.

The responsibility for performing specific functions in an LFM impacts system architecture, device prequalification, and market design [107]. Our taxonomy distinguishes between the flexibility platform operator and third-party operators for this responsibility. This clarity is crucial, especially for functions like activation, where ambiguity can result in task failure. Currently, no set approach for activation exists; it can be market-based (via the market operator (MO)) or directly controlled (via the SO) [8]. This may change with the forthcoming EU demand response framework, specifying the SO's role in bid selection, activation, and service control (see paragraph (62) in [29]).

We outline five dimensions in the computation category. The first, the input dimension, considers whether a function requires single or multiple information sources. This affects architecture and scalability [72,108]. The second, the trigger dimension, categorizes functions as manual or automatic, noting that semi-automatic functions are considered manual. The third dimension deals with time constraints on computations, which we classify broadly as defined or undefined. The fourth, execution, examines whether the function operates in real-time, near real-time (e.g., within 15 min), or batch (e.g., for payment) mode. Lastly, the resource dimension qualitatively identifies resource consumption as low, medium, or high, given the fast-changing nature of technology and the prior author's experience with quantification [108].

Table 6
Taxonomy based on the function interoperability layer.

Category	Dimension	Characteristic						ME
Objective	Scope	Assessment	Trading	Communication	Dispatch	Activation	Validation & settlement	Yes
Management	Responsible	System operator			Third-party operator			Yes
Computation	Input	Single			Multiple			Yes
	Trigger	Manually			Automatically			Yes
	Time limitation	Defined			Undefined			Yes
	Execution	Real-time		Near real-time		Batch		Yes
	Resources	Low demanding		Medium demanding		High demanding		Yes

4.3. Information interoperability layer

Table 7 describes the taxonomy for the information interoperability layer. The information taxonomy has three categories, three dimensions, and eleven characteristics, making it the shortest of all five interoperability layers taxonomies. Even though its relatively short aspect, it complies with the recommendations from [74,75]. The taxonomy provides relevant insights concerning the information, structure, contents, and how to use it. We recommend that practitioners consider the following steps when utilizing the taxonomy:

1. identify each link,
2. classify each link using the taxonomy.

In other words, we propose to describe each link, with each representing a connection between different nodes (components), thus being similar to the function taxonomy. The complexity of this exercise reduces when using a SGAM mapping as the primary input for the taxonomy. Authors in [108] provide examples of identified link descriptions for the information interoperability layer.

We identify three main categories for the information interoperability layer taxonomy, each having a single dimension. The first category concerns the data model employed, which refers to how the data was wrapped. Examples include asset metering models like IEC 62056 [109], flexibility models such as energy flexibility data model (EFDM) [110], and market data models like USEF's USEF Flex Trading protocol (UFTP) [111]. Given the diversity of data models, we include general characteristics for resilience in our taxonomy. The second category, content, differentiates among three characteristics: technical–electrical (e.g., power, voltage, holding duration), market (e.g., price, bid size, price cap, contract duration) [112], and support information (e.g., grid data via common information model (CIM)). Our approach aligns with the framework in [113]. The third category focuses on data treatment. The interviewees emphasized the role of cyber security in LFM solutions, underscoring its importance in the context of data exchange and general data protection regulation (GDPR) [114]. Our taxonomy addresses this by including a data sensitivity category, guided by National Institute of Standards and Technology (NIST) and Confidentiality, Integrity and Availability (CIA) frameworks [115,116].

4.4. Communication interoperability layer

Table 8 provides a communication interoperability taxonomy inspired by selective layers of the Open Systems Interconnection (OSI) model [117]. This selection emerged from targeted interviews. Although resembling the Transmission Control Protocol/Internet Protocol (TCP)/Internet Protocol (IP) model [118] and Enhanced Performance Architecture (EPA), our taxonomy accommodates smart grid-specific protocols like S0 used for Remote Terminal Unit (RTU) communication [108]. Similar to the function and information layer, we recommend practitioners should:

1. identify each link,
2. classify each link using the taxonomy.

For the data transport category, we focus on the end-to-end reliability dimension and distinguish between two key characteristics: acknowledgment, exemplified by TCP, and no acknowledgment, exemplified by User Datagram Protocol (UDP).

For the network infrastructure category, we identify two dimensions: management and coverage. Management is further categorized into public and private networks, while the coverage dimension follows the Smart Grid Coordination Group classification, aligning with SGAM concept (see Figure 16 — Mapping of communication networks on the SGAM. [20]).

For the communication technologies category, we identify three descriptive dimensions: Latency, divided into time-sensitive, which refers to the time limit for communication as crucial, and non-time-sensitive; Medium, representing either wireless or wired technologies; and Raw Data Rate, described qualitatively as low, medium, or high. Given the rapid pace of technological change, we opt for a qualitative approach (low, medium, or high). This approach allows practitioners to describe their systems within the context of this taxonomy effectively.

For the application protocol category, we focus on one dimension: message-coupling. We identify two characteristics: client–server and publish–subscribe. The client–server model features a hierarchical structure where information flows directly from server to client. In contrast, the publish–subscribe model is non-hierarchical, involving a broker to mediate information exchange between publishers and subscribers.

Lastly, we considered interoperability as a category, given its importance in smart grids [119]. To simplify such a complex category, we hone in on protocol standardization, addressing the core issue of technical interoperability [120]. We differentiate between open protocols that allow user implementation and proprietary ones that restrict usage and conceal internal details.

4.5. Component interoperability layer

Table 9 presents a taxonomy for the LFM component interoperability layer, blending power components like electrical networks with devices or tools. We recommend practitioners use it as an overarching solution description, aligned with SGAM, rather than isolating each component for LFM use cases. We advise practitioners to follow these steps:

1. select the characteristic for the electrical network category;
2. identify each component for classification;
3. classify each tool identified based on the tools category.

However, we suggest choosing only the relevant categories for those who wish to apply the taxonomy to individual components, excluding the electrical network.

The first category is the electrical network. Electrical location matters for flexibility provision as it influences power flow and line conditions. We categorize network structures into meshed, radial interconnected, and radial. Meshed networks offer multiple paths for reliability. We consider ring structures to be simplified mesh networks. Radial interconnected structures are hierarchical but have reconfiguration devices for some merging. Radial networks are common and straightforward, with all elements stemming from a substation.

Flexibility assets are the sources of flexibility. They are units capable of changing their operation following a signal. They play a central role in LFM, as congestion problems are location-specific, and solving congestion could require a specific flexibility source (load, generation, or storage) and a specific voltage connection level (LV, MV, HV). We do not distinguish between market roles (such as generation, consumer,

Table 7
Taxonomy based on the information interoperability layer.

Category	Dimension	Characteristic					ME
Container	Data model	Asset metering	Flexibility	Market	Asset control	Not specified	Yes
Content	Focus	Technical-Electrical	Market information	Support information			Yes
Data treatment	Sensitivity	Public	Confidential/Private	Restricted			Yes

Table 8
Taxonomy based on the communication interoperability layer.

Category	Dimension	Characteristic			ME
Data transport	Reliability	Acknowledgment	No acknowledgment		Yes
Network infrastructure	Management	Public	Private		Yes
	Coverage	SGAM – List			Yes
Communication technologies	Latency	Time sensitive	Non time sensitive		Yes
	Medium	Wireless	Wired		Yes
	Raw data rate	Low	Medium	High	Yes
Application protocol	Message-coupling	Client-Server	Publish-Subscribe		Yes
Interoperability	Protocol standardization	Open	Proprietary		Yes

Table 9
Taxonomy based on the component interoperability layer.

Category	Dimension	Characteristic			ME
Electrical network	Structure	Meshed	Radial interconnected	Radial	Yes
Flexibility asset	Flexibility source	Load	Generation	Storage	No
	Voltage connection	LV	MV	HV	No
Metering & Control	Device	Smart meter	IED - Off the shelf	IED - Specific	No
Tools	Computational location	On-premise (Local)	Cloud based (Third-party)		Yes
	Data storage	Centralized	Decentralized		Yes

or prosumer) as we only focus on the asset type for the component interoperability taxonomy.

In LFM, device measurement and control are key aspects, as highlighted in Sections 4.1 and 4.2. We categorize this under a single abstract dimension: the device. We split it into two categories: smart meters, intelligent electrical device (IED)-off-the-shelf or IED-specific. Smart meters are essential for data collection and validation but not for all flexibility assets. Some solutions use custom devices (IED-specific), while others opt for off-the-shelf to improve technical interoperability.

Finally, our taxonomy highlights tools as essential components for task execution, focusing on two primary dimensions: computational location and data storage. Computational location can be either on-premise or cloud-based. When computational power is provided by internal servers belonging to the tool's owning organization, we categorize it as on-premise. This distinction is important for assessing varying physical and cyber security requirements. Data storage is another crucial dimension, particularly given the rise in data sensitivity issues. We identify two types of storage: centralized and decentralized. In centralized storage, the data remains within the organization. In contrast, decentralized storage involves external systems like third-party cloud services or Distributed Ledger Technologies (DLTs) [121]. This is relevant for practitioners considering data storage options and their associated technological challenges.

5. Taxonomy examples

This section showcases the practical application of the taxonomy through various use cases, including a detailed one involving the DSO Electricity North West Ltd. (ENWL) and Piclo's LFM solution. Three more use cases are in Appendix C, covering diverse contexts like different countries, market platforms, and regulations. These additional examples include a UK case with NGED's Flexible Power, a Dutch case focusing on Grid Operators Platform for Congestion Spreads (GOPACS) and local DSO Enexis, and a Spanish case featuring an LFM solution by OMIE.

5.1. United Kingdom - electricity north west - Piclo

ENWL, a UK DNO transitioning to a DSO [122,123], oversees 57,000 km of power lines and runs biannual Invitation to Tender (ITT) for local flexibility services. Their current tenders (so-called competitions) aim to procure local flexibility through a three-stage process: pre-tender, tender, and post-tender [124]. These are hosted on the Piclo Flex platform, an online marketplace for energy flexibility [63]. The latest ITT for Spring 2023 targets 1097 MW of flexibility across 32 locations with a £ 10.1 m budget spanning 2023–2028 [125]. Subsequent sections will focus on this specific tender.

Our analysis centers on three specific competitions: ENWL-229, ENWL-230, and ENWL-238, omitting new developments by Piclo [126]. The first two target Dynamic and Restore services in Alston, while the latter focuses on Secure service in Bolton By Bowland. We examine a representative contract for each area to elucidate the taxonomy.

1. ENWL-229/Alston (Dynamic) W23/24 - All Day,
2. ENWL-230/Alston (Restore) FY24 - All Day,
3. ENWL-238 Bolton By Bowland (Secure) W27/28 - All Day.

The details of site-specific requirements and service parameters are available in [127] and the flexibility map of the Piclo Flex platform [128].

5.1.1. Business interoperability layer taxonomy

Table 10 presents a business taxonomy for each selected competition, noting that all deal with unplanned congestion management needs. Specifically, ENWL-238 targets pre-fault needs, while ENWL-229 and ENWL-230 focus on post-fault needs. The primary difference between the latter two is that ENWL-230 emphasizes flexibility during network re-energization caused by abnormalities.

In each competition, the DSO is the flexibility buyer, with FSPs participating individually or in aggregated units. The market operator is Piclo, an independent entity. The bidding window runs from July 10 to 21, 2023, for service delivery between November 2023 and March 2028. In our taxonomy, ENWL-238 is categorized as "long-term" due to its October 2027 delivery, while the other contracts start in November 2023. The DSO seeks at the MV (11 kV) and LV (0.24 kV) levels. FSPs must first pass the market and then the technical prequalification steps on the Piclo platform to participate. The market requires FSPs to register on the Dynamic Procurement System (DPS), a company qualification assessment [129], while for the technical, they need to fill in a Prequalification Questionnaire on the Piclo platform.

The three competitions have similar product attributes, as standardized by the Energy Networks Association (ENA). These attributes include not exclusive: minimum flexibility capacity, frequency of use, and ramping period. All competitions seek upward active power and share the same market-clearing design, operating in a one-sided market with DSO as the single buyer. The competitions differ mainly in their remuneration structure: ENWL-229 favors higher energy payments, ENWL-238 emphasizes capacity payments, and ENWL-230 offers only

Table 10
Business interoperability layer taxonomy for the three service products in the UK Electricity North West offers in Piclo.

Category	Dimension	NWL-238/Bolton By Bowland (Secure)		ENWL-229/Alston (Dynamic)		ENWL-230/Alston (Restore)	
CM need	Origin	Unplanned (pre-fault)		Unplanned (post-fault)		Unplanned (restoration)	
Participants	Flexibility buyer	DSO		DSO		DSO	
	Flexibility service provider	Aggregator	Individual provider	Aggregator	Individual provider	Aggregator	Individual provider
	Market operator	Independent commercial		Independent commercial		Independent commercial	
Market scope	Negotiation time frame	Long-term		Mid-term		Mid-term	
	Flexibility need (grid level)	DSO MV	DSO LV	DSO MV	DSO LV	DSO MV	DSO LV
	Offer organization	Congestion zone/s		Congestion zone/s		Congestion zone/s	
Market access	Prerequisites	Technical	Market	Technical	Market	Technical	Market
Product	Attributes (Parameters)	Standardized at country level		Standardized at country level		Standardized at country level	
	Transactional object	Energy (Activation)	Capacity (Availability)	Energy (Activation)	Capacity (Availability)	Energy (Activation)	
	Power	Active Power		Active Power		Active Power	
	Direction	Upwards		Upwards		Upwards	
Clearing	Matching	Call market (Tender)		Call market (Tender)		Call market (Tender)	
	Demand/Supply formation	One side Market		One side Market		One side Market	
	Grid constraint representation	Bid limitation		Bid limitation		Bid limitation	
	Pricing rule	Pay-as-bid		Pay-as-bid		Pay-as-bid	
Metering verification	Flexibility unit metering	Asset	Portfolio	Asset	Portfolio	Asset	Portfolio
	Baseline method	Historical data	Alternative data	Historical data	Alternative data	Historical data	Alternative data
Integration	External coordination	Does not implement coordination		Does not implement coordination		Does not implement coordination	
	Existing market interaction	Undefined		Undefined		Undefined	
Economic	Fees	Fixed	Variable	Fixed	Variable	Fixed	Variable

Table 11
Function taxonomy for the flexibility assessment and clearing functions.

Category	Dimension	Characteristic - Flexibility Assessment	Characteristic - Clearing
Objective	Scope	Assessment	Trading
Management	Responsible	System operator	Third party operator
Computation	Input	Multiple	Multiple
	Trigger	Manually	Automatically
	Time limitation	Undefined	Undefined
	Execution	Batch	Batch
	Resources	High demanding	Medium demanding

a premium energy payment. The Piclo Flex platform clears the market based solely on FSPs bids, with no grid information considered. Payments follow a pay-as-bid system until the DSO meets its requirements or reaches the area's budget limit.

ENWL measures at the point of supply, requiring each FSP to offer minute-by-minute asset data. ENWL uses various baseline methods like Mid 8-in-10 (uses data from the middle of the last 8 of 10 days); Mid 8-in-10 with Same Day Adjustment; Mid X-in-Y (the user can choose how many days to consider and the length of same day adjustment), Nominated (self-declared baseline of the asset in advance of the flexibility dispatch event) and Zero (assumes that the asset is not operating except for when providing a flexible service). Consequently, our taxonomy includes historical and alternative data as characteristics of the baseline dimension.

The Piclo platform is an independent marketplace without external market coordination or links to existing markets like intraday or day-ahead. Both the DSO and FSP incur fixed platform fees, and FSPs may face variable fees for partial or non-fulfillment of contracts.

5.1.2. Function interoperability layer taxonomy

From a functional point of view, we focus on three key functions: flexibility assessment, clearing, and order dispatch, selected based on interview insights and remarks by authors in [31]. These functions operate consistently across different products and competitions. Table 11 and Table 12 provide a taxonomy tailored for classifying these functions.

The flexibility assessment function, managed by ENWL, identifies and quantifies areas requiring flexibility to alleviate congestion. This involves gathering data, including forecasts and substation data. Typically executed in a resource-intensive batch process, this function is manually triggered without a set time frame (batch process).

The clearing function, managed by the Piclo platform, matches FSPs offers with DSO flexibility needs specified in the tender. After clearing, Piclo informs the DSO of the matched bids, although the final bid selection is a two-stage and two-company process inherited from their design. The clearing is an automated process with multiple inputs, executed after post-bidding, and operates in a batch mode without real-time constraints, requiring medium-level resources.

The dispatch activation function in Table 12, handled by the DSO on the Piclo platform, sends dispatch signals of winning bids to FSPs for all power products and competitions. We assume the following: it is a manual process with a single input—the output from the clearing stage. Time-sensitive and critical, it varies in execution: "secure" products are dispatched in batches a week ahead, while "dynamic" and "restore" are near real-time, triggered as needed. This function requires low resources, primarily for communication.

5.1.3. Information interoperability layer taxonomy

We used a dispatch signal as an example for our information taxonomy represented in Table 13. We assume after speaking with Piclo managers that the DSO sends the dispatch signal to the FSP through the Piclo platform using a JavaScript Object Notation (JSON) schema known as an "obligation". We considered it as "asset control" in our taxonomy; this signal includes both technical and support details. Technical information covers start/end times, capacity, and direction. Support information includes identifiers for both DSO and FSP, obligation ID, request for response, and signature. Given that it contains sensitive identifiers, the dispatch signal is considered confidential.

5.1.4. Communication interoperability layer taxonomy

Likewise, we examined the communication link between the DSO and FSP for dispatching signals in Table 14. The link uses Internet-based webhooks triggered by events and follows the standard TCP/IP

Table 12
Function taxonomy for the dispatch function.

Category	Dimension	Characteristic - Secure	Characteristic - Dynamic	Characteristic - Restore
Objective	Scope	Dispatch	Dispatch	Dispatch
Management	Responsible	System operator	System operator	System operator
Computation	Input	Single	Single	Single
	Trigger	Manually	Manually	Manually
	Time limitation	Defined	Defined	Defined
	Execution	Near real-time	Near real-time	Near real-time
	Resources	Low demanding	Low demanding	Low demanding

Table 13
Information taxonomy for the dispatch signal.

Category	Dimension	Characteristic	
Container	Data model	Asset control	
Content	Focus	Technical-Electrical	Support
Data treatment	Sensitivity	Confidential/Private	

Table 14
Communication taxonomy for the dispatch signal communication link.

Category	Dimension	Characteristic	
Data transport	Reliability (end-to-end)	Acknowledgment	
Network infrastructure	Management	Public	
	Coverage	DSO market backhaul	FSP market backhaul
Communication technologies	Latency	Time sensitive	
	Medium	Wire	
	Raw data rate	Low	
Application protocol	Message-coupling	Client-Server	
Interoperability	Protocol standardization	Open	

Table 15
Component taxonomy.

Category	Dimension	Characteristic	
Electrical network	Structure	Radial	
Flexibility asset	Flexibility source	Load	Generation
	Voltage connection	LV	MV
Metering & Control	Device	Smart meter	IED - Off the shelf
Tools - Dispatch	Computational location	Cloud based (Third-party)	
	Data storage	Decentralized	

model. Acknowledgment is required for data transport. Given its use of the Internet, the link has extensive coverage, referred to as the backhaul connection. We assume it is a wired link with a low data rate. The dispatch signals are time-sensitive, requiring low latency. The communication uses a client–server architecture with message coupling.

5.1.5. Component interoperability layer taxonomy

Table 15 presents the taxonomy for the component interoperability layer. We assumed a radial electrical LV and MV network, commonly found in Europe [130]. ENWL seeks flexibility from load and generation sources at these voltage levels. We excluded storage systems due to uncertainty. Smart meters and IEDs are essential for metering and control. The dispatch tool from Piclo, which uses a third-party cloud. According to Piclo's engineers (whom we approached), the data is decentralized across several servers.

6. Discussion and recommendations

This section synthesizes key insights and recommendations. These are drawn from the work conducted in this paper: literature and project review and analysis, expert interview comments, and the taxonomy instantiation over various LFM design solutions across Europe.

6.1. Taxonomy insights

First, the approach of organizing the taxonomy into five layers, aligned with the SGAM framework, streamlines the interpretation of LFM solutions from multiple perspectives. This approach not only highlights market-specific considerations but also reveals these solutions' intrinsic nuance differences in their characteristics. We observe that this approach has four key advantages: (1) it provides a holistic overview of the solutions, (2) it facilitates the rapid identification of pertinent discussion topics across academic, industrial, and regulatory stakeholders, and (3) it allows for the mapping of design principles to specific layers within the multi-tiered taxonomy. For example, market neutrality and product design principles are closely linked with the business layer, operational responsibilities correspond with the function layer, and issues of data clarity and interoperability resonate with the ICT layers of the taxonomy.

Second, while all the LFMs solutions analyzed in Section 5 and Appendix C operate under a common conceptual framework and aim to develop and use a platform-based LFM solution, our taxonomy unveils subtle yet impactful differences, as earlier inferred. These distinctions often arise from a similar congestion management challenge that SOs face, but they implement different solutions to solve it. We found this diversity even within the same jurisdiction, such as the UK, where competing solutions adopt similar but nuanced approaches. For instance, some solutions employ distinct remuneration schemes for energy and capacity to address specific grid congestion issues, thereby influencing their overall design. Another salient example is the disparate management of the market-clearing function: one solution employs a third-party operator, while the other utilizes a SO. These observed variances underscore the necessity for a holistic taxonomy that highlights and contextualizes these nuances in a harmonized format applicable to these solutions.

Third, the choice of MO significantly shapes the governance dynamics of these LFMs solutions. Opting for either a third-party entity or the SO as the MO brings its own set of advantages and drawbacks. A third-party operator may strengthen market neutrality but necessitates intricate coordination mechanisms for effective data sharing among stakeholders, particularly regarding network-related information, in a highly network-location-dependent problem. Contrariwise, designating the SO as both MO and flexibility buyer allows for the seamless integration of network constraints into the LFM market clearing system. It enhances the coordination and efficiency in procuring and operating flexible resources but opens the market question of market neutrality.

Fourth, the design of these LFMs solutions can be viewed as either restrictive or liberating depending on the vantage point, whether it be the FSP, SO, or any third-party. For example, unrestricted technical market access may be favorable for attracting more FSPs. However, it could counterproductively diffuse the SO's efforts to resolve specific grid congestion challenges. The instantiated taxonomies also enlighten the delicate balance required in formulating market penalties that can discourage FSP participation while ensuring grid security from the SO's perspective. Additionally, certain design choices, such as the directionality of power flexibility, may be regulatory constraints that limit market participation. Yet, the necessity of such directionality is contingent on the actual needs of the flexibility buyer. Another aspect warranting attention is the impact of pricing rules on DSO. Typically, DSO revenues are a function of customer count and regulated network tariffs. Design characteristics like utilizing a pay-as-clear market pricing rule may result in uniform payments across FSPs, despite variances in their technical impact on the network, thus potentially escalating costs for the DSO. Nevertheless, the comprehensiveness of the taxonomy can aid stakeholders in recognizing and articulating these inherent design trade-offs, reinforcing that no stakeholder is unduly favored in the LFM solution design.

Fifth, a notable concern is that many LFMs currently operate isolated and detached from existing power markets, which poses potential risks to market liquidity and long-term viability. To mitigate these challenges, some regions have pursued unique strategies. For example, in Spain, there is a natural integration with pre-established electricity markets due to shared operational agents (OMIE). Another avenue is to build interconnections within internal LFM markets, as demonstrated by Flexible Power, where non-fulfillment of long-term contracts automatically activates shorter-term agreements. Nonetheless, the full efficacy of these approaches can only be validated through analysis in the coming years as they operate.

Sixth, the product definition is central to the architecture of LFM solutions. Standardization of well-defined products has been observed to accelerate the evolution of LFM markets, as exemplified by operational markets in the United Kingdom and the Netherlands.

Finally, our last insight underscores the potential need to periodically review the taxonomy as policies and specific characteristics of LFM solutions become more defined through forthcoming guidelines and national regulations.

6.2. Recommendations

We propose the following recommendations from the previously derived observations and insights that can guide practitioners.

1. Theoretical framework limitations: While the SGAM framework has been instrumental in structuring our taxonomy, it has certain limitations, especially in accommodating market-driven elements in only one unique layer (i.e., business), aligning with observations by Paustian et al. [131]. Both our study and theirs advocate for revising the SGAM to better accommodate market-driven paradigms.
2. Unique taxonomy layer design: Our multi-layered taxonomy can serve as a foundational structure that could be adapted for other taxonomies-oriented services, other taxonomies (i.e., local electricity markets), or ontologies of congestion management services. A single-layered taxonomy might not be practical or optimal due to the numerous design characteristics inherent in LFM solutions.
3. Addressing information gaps: We found a notable lack of information outside the business taxonomy layer, such as communication protocols and device requirements. To mitigate this, we recommend utilizing the comprehensive taxonomy to enhance the depth of documentation, thereby augmenting the transparency and accessibility of LFM solutions.
4. Consideration of several design principles: Given the power system structures and many different points of view, we recommend considering these points of view to collect the market design principles for developing solutions as otherwise solutions that do not feature these principles may face challenges and a lack of support from other stakeholders. For instance, Europex is a power exchange association that advocates for facilitating transparent and neutral market operations, openness to different flexibility resources, straightforward product design, adaptability to local needs, integration with existing markets, and responsibility and incentive schemes for cost-effective system management principles to be included in LFM solutions [132].
5. Clarification of Governance and Operational Models: Upcoming regulations should clarify both high-level and granular roles and responsibilities. This would offer guidelines applicable to both SO-managed and third-party-managed LFMs.
6. Push for market integration and liquidity: We recommend the development of mechanisms that allow cross-platform integration and multi-service provisioning in LFMs as one additional solution to the currents previously explored. This approach is likely to enhance market liquidity and is congruent with broader energy market objectives, albeit it necessitates comprehensive research, validation, and investment.
7. Product Definition and Standardization: A minimum set of attributes should be defined as a template for all products, allowing ad-hoc attributes to be added as specific needs arise.
8. Periodic Update: Taxonomies should be dynamic, not static, adapting to emerging new objects [75]. Hence, our final recommendation is to review the taxonomy in the coming years. Since our recommendations are based on a period where LFM solutions, with a focus on congestion management, are still in development — and considering guidelines like those from ACER — it would be prudent to revisit the taxonomy after a few years, especially after the demand response framework guidelines and the appearance of regulation from different jurisdictions.

7. Conclusion

The development of local flexibility markets platform solutions is a rapidly growing and complex area within smart grid solutions. We have created a comprehensive, multi-layer taxonomy to understand better and analyze these solutions. Our multi-layer taxonomy contribution strives to describe, classify, and analyze local flexibility market platforms, explicitly focusing on congestion management at the distribution layer and consequently reducing the information fragmentation of information to be used when describing these solutions.

We developed the multi-layer taxonomy following an iterative process involving sixteen iterations. We considered a range of projects, online documentation, expert opinions, and academic literature to ensure that our multi-layer taxonomy was comprehensive and accurate. The result is a five-layer taxonomy that aligns with the Smart Grid Architecture Model framework. This multi-layer taxonomy provides a complete classification of local flexibility market platforms, facilitating a deeper understanding of their design characteristics.

To demonstrate the applicability of our multi-layer taxonomy, we have provided a complete example, focused on the Piclo local flexibility market platform solution currently operating in the United Kingdom. Additionally, we have included three additional examples of use cases from the United Kingdom, the Netherlands, and Spain. These examples highlight the versatility and relevance of our taxonomy in capturing the complexity of local flexibility market platform solutions. This is particularly the case in the context of congestion management at the distribution level.

As highlighted in the discussion section, local flexibility markets solutions evolve continually, and our taxonomy serves as a foundational block for further exploration and analysis. As the landscape of local flexibility markets expands in the future to include other services, our taxonomy provides a solid basis to accommodate the increased complexity that may arise. By offering a structured and comprehensive approach, our taxonomy contributes to advancing knowledge and understanding of local flexibility market solutions. This will support informed decision-making, and foster innovation in the pursuit of efficient and reliable smart grid systems.

CRediT authorship contribution statement

Sergio Potenciano Menci: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Orlando Valarezo:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation.

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.

Data availability

The authors do not have permission to share data.

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Appendix A. Taxonomy-building method steps

For clarity and convenience, we include Fig. A.1 in our appendix. We have taken it from [74], and it illustrates the sequential process necessary for constructing a taxonomy.

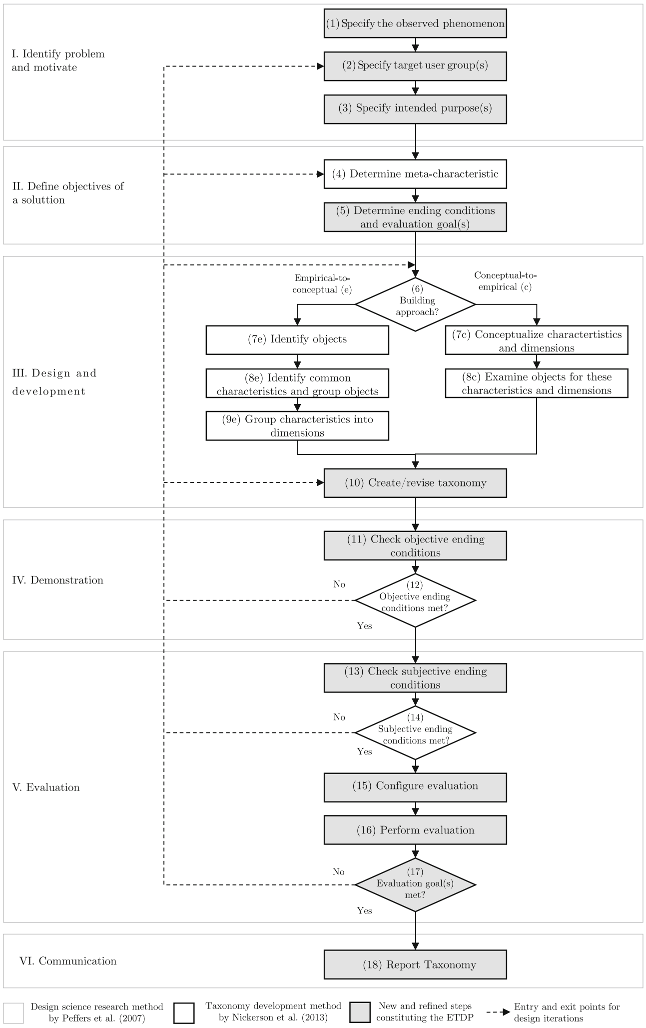

Fig. A.1. Extended taxonomy design process (ETDP) taken from [74].

Appendix B. Evaluation questions

See Table B.1.

Appendix C. Additional taxonomy examples

C.1. United Kingdom - national grid - flexible power

NGED, rebranded from Western Power Distribution in September 2022, operates as both a DNO and DSO in various regions. In 2018, they began procuring flexibility services through bi-annual tenders. We examined their 2022 s cycle tender, which ran from June 27 to October 3, 2022, and aimed to procure 297.69 MW of flexibility across 47 locations for contracts lasting one to four years. From these locations and contracts, we analyzed in detail the following two:

1. Grassmoor - Chesterfield (Secure),
2. Aberaeron - Ceredigion (Dynamic)

C.1.1. Business taxonomy

We provide in Table C.2 the business layer taxonomy for the 2022 tendering process second cycle.

NGED uses their tender process to address potential network congestion issues, targeting both winter and summer constraints up to 2027. While the Grassmoor-Chesterfield area focuses on pre-fault needs,

Table B.1
Overview of the battery of questions for the evaluation criteria.

Criteria [84,85]	Questions	Definition of evaluation criteria [74]
Completeness	Do you believe the taxonomy is now complete?	The degree to which the structure of the artifact contains all necessary elements and relationships between elements.
Ease of use	Is the taxonomy easy to use?	The degree to which the use of the artifact by individuals is free of effort.
Simplicity	Does it cover the essentials?	The degree to which the structure of the artifact contains the minimal number of elements and relationships between elements.
Understandability	Is it understandable?	The degree to which the artifact can be comprehended, both at a global level and at the detailed level of the elements and relationships inside the artifact.
Fidelity with real-world	Can it help analyze LFM solutions focused on congestion management in the EU?	The degree to which the structure of the artifact corresponds to the modeled reality.
Consistency	Can it help to describe, understand, and classify real-world and upcoming solutions?	Results from the ratio of completeness and simplicity.
Level of detail?	Does it cover a sufficient degree of detail	Results from the ratio of completeness and simplicity.
Robustness	Is it robust enough for you to allocate information across the layers?	The ability of the artifact to handle invalid inputs or stressful environmental conditions.

Table C.2
Two service products business taxonomy from NGED in the UK.

<table>
<tr><th>Category</th><th>Dimension</th><th colspan="2">Characteristic - Grassmoor - Chesterfield (Secure)</th><th colspan="2">Characteristic -Aberaeron - Ceredigion (Dynamic)</th></tr>
<tr><td>CM need</td><td>Origin</td><td colspan="2">Unplanned (pre-fault)</td><td colspan="2">Unplanned (post-fault)</td></tr>
<tr><td rowspan="3">Participants</td><td>Flexibility buyer</td><td colspan="2">DSO</td><td colspan="2">DSO</td></tr>
<tr><td>Flexibility service provider</td><td>Aggregator</td><td>Individual provider</td><td>Aggregator</td><td>Individual provider</td></tr>
<tr><td>Market operator</td><td colspan="2">Network operator</td><td colspan="2">Network operator</td></tr>
<tr><td rowspan="3">Market scope</td><td>Negotiation time frame</td><td colspan="2">Long-term</td><td colspan="2">Long-term</td></tr>
<tr><td>Flexibility need (grid level)</td><td colspan="2">DSO MV</td><td colspan="2">DSO MV</td></tr>
<tr><td>Offer organization</td><td colspan="2">Congestion zone/s</td><td colspan="2">Congestion zone/s</td></tr>
<tr><td>Market access</td><td>Prerequisites</td><td>Technical</td><td>Market</td><td>Technical</td><td>Market</td></tr>
<tr><td rowspan="4">Product</td><td>Attributes (Parameters)</td><td colspan="2">Standardized at country level</td><td colspan="2">Standardized at country level</td></tr>
<tr><td>Transactional object</td><td>Energy (Activation)</td><td>Capacity (Availability)</td><td colspan="2">Energy (Activation)</td></tr>
<tr><td>Power</td><td colspan="2">Active Power</td><td colspan="2">Active Power</td></tr>
<tr><td>Direction</td><td colspan="2">Upwards</td><td colspan="2">Upwards</td></tr>
<tr><td rowspan="4">Clearing</td><td>Matching</td><td colspan="2">Call market (Tender)</td><td colspan="2">Call market (Tender)</td></tr>
<tr><td>Demand/Supply formation</td><td colspan="2">One side Market</td><td colspan="2">One side Market</td></tr>
<tr><td>Grid constraint representation</td><td colspan="2">Bid limitation</td><td colspan="2">Bid limitation</td></tr>
<tr><td>Pricing rule</td><td colspan="2">Pay-as-clear</td><td colspan="2">Pay-as-clear</td></tr>
<tr><td rowspan="2">Metering verification</td><td>Flexibility unit metering</td><td>Portfolio</td><td>Asset</td><td>Portfolio</td><td>Asset</td></tr>
<tr><td>Baseline method</td><td>Historical data</td><td>Alternative data</td><td>Historical data</td><td>Alternative data</td></tr>
<tr><td rowspan="2">Integration</td><td>External coordination</td><td colspan="2">Does not implement coordination</td><td colspan="2">Does not implement coordination</td></tr>
<tr><td>Existing market interaction</td><td colspan="2">Undefined</td><td colspan="2">Undefined</td></tr>
<tr><td>Economic</td><td>Fees</td><td colspan="2">Variable</td><td colspan="2">Variable</td></tr>
</table>

Aberaeron-Ceredigion deals with post-fault scenarios. Both rely on NGED as the DSO, market operators and flexibility buyers, working with aggregators and individual providers through the Flexible Power platform. Our focus was on long-term contracts for Secure and Dynamic services in 2022, but NGED plans to fulfill remaining needs through shorter-term products. For example, they require 2.73 MW in Grassmoor-Chesterfield and 0.74 MW in Aberaeron-Ceredigion. Unmet longer-term needs will trigger a short-term market. The flexibility grid level varies by area but both analyzed locations require DSO MV flexibility. NGED has specific technical and market criteria for FSPs to participate in their flexibility tenders. At the same time, they share similarities with ENWL's taxonomy (Section 4), NGED like DPS, it employs adapted terms, like Pre-Qualification Questionnaire (PQQ).

Concerning the product, the taxonomy is the same as ENWL's business taxonomy in Section 5.1. In the UK, the attributes are standardized at the country level, with the technicality that NGED uses adapted terminology for the same concepts. Both competitions seek upward active power using a call market approach for long-term contracts, driven by the DSO (one-sided market). In these cases, the grid representation is also limited to the bid information following a pay-as-clear pricing rule. However, it is necessary to note that NGED also has maximum selling prices for each product type and area. For example, for 2023 the Grassmoor (Secure) area and their long-term flexibility has a capacity (availability) selling price of £1252/MWh and an energy (activation or utilization) ceiling price of £1753/MWh.

For metering and verification, NGED utilizes Flexible Power, requiring FSPs to form dispatch groups with one or multiple meterable units per congestion area. These units can be single or aggregated assets. In our taxonomy, we categorize these as either *portfolio* or *asset*. NGED mainly uses historical data for baselines, calculating average demand from the past month's first three weeks and using the last 75 h for generators.

Regarding integration and fees, like ENWL, NGED operates in isolation with no external market interaction. Fees are variable and act as penalties; FSPs see payment reductions based on delivery accuracy.

C.1.2. Function taxonomy

Regarding the function taxonomy, we provide three examples of different functions in Table C.3. The classification applies to any of the 47 locations where the tender process occurs, including the area of Grassmoor - Chesterfield (Secure) and Aberaeron - Ceredigion (Dynamic).

The flexibility assessment function, conducted by the DSO, involves multiple internal steps, including network impact assessments and cost–benefit analyses, as detailed in [133]. We assume it to be manually triggered and resource-intensive, requiring various scenarios for optimal operation.

The clearing function, managed by the DSO, we assume to have multiple inputs and automatically triggers as competitions close, given the limited online information available. Furthermore, we assume it places medium resource demands by comparing and ranking bids based on price and that there is no specified time limit for its execution.

NGED manages the order dispatch function consistently across all competition types and time frames. We assume, an operator manually triggers this function and has a single input. It has a 15-minute time limit for execution ahead of activation. Due to its near-real-time requirement, it places low demands on resources.

C.2. The Netherlands - Enexis

Enexis, one of the seven primary DSOs in the Netherlands, uses two solutions for local flexibility: their own Grid and Management Service (GMS) [19] and the widely-used GOPACS [60]. The latter is not technically a market platform as remarked in [31,134] but is significant for short-term congestion management in the Dutch market. We included a taxonomy for Enexis for two reasons: to test if our taxonomy can apply to solutions not traditionally considered as LFM, and to help Enexis align (prescription) its GMS or the GOPACS solution with upcoming demand-response frameworks from ACER.

C.2.1. Business - GOPACS

In the Enexis case study using GOPACS, we outline a business taxonomy in Table C.4. GOPACS serves as a short-term, unplanned congestion management solution involving Enexis, aggregators, and flexibility providers. Despite lacking a traditional market operator, GOPACS relies on ENERGY TRADING PLATFORM AMSTERDAM (ETPA) [135] or potentially EPEX SPOT in the future [136], leading us to categorize the market operator dimension as *independent regulated*.

In the case of GOPACS, the short-term negotiation focuses on unplanned flexibility needs. FSPs must meet technical and market prerequisites to participate. Technically, they must obtain a Congestion management Service Provider (CSP) approval from Tennet, the TSO, and undergo a DSO-led pre-qualification for each congestion point. Unlike other systems, no physical tests (ex-ante) are required in prequalification. Market-wise, FSPs must register with Energie Data Services Nederland (EDSN) and sign the intra-day congestion spreads (IDCONS) participation agreement, providing a list of 18-digit European article numbering (EAN) codes that identify electrical connections. They must also have an agreement with a market connected to GOPACS, currently ETPA.

In GOPACS, the only available product is IDCONS, which is not standardized at a national level, unlike in the UK. An IDCONS must specify power, time of use, price, and, importantly, the EAN code. It remunerates solely based on declared energy. An IDCONS comprises an order and a contra-order, which balances the system. The price difference between these orders is termed "the spread", covered by

Table C.3
Function taxonomy for three different functions.

Category	Dimension	Characteristic - Flexibility Assessment	Characteristic - Clearing	Characteristic - Order dispatch
Objective	Scope	Assessment	Trading	Dispatch
Management	Manager	System operator	System operator	System operator
Computation	Input	Multiple	Multiple	Single
	Trigger	Manually	Automatically	Manually
	Time limitation	Undefined	Defined	Defined
	Execution	Batch	Batch	Near real-time
	Resources	High demanding	Medium demanding	Low demanding

Table C.4
Short-term service LFMs business taxonomy from Enexis in the Netherlands.

Category	Dimension	Characteristic – GOPACS Short-term	
CM need	Origin	Unplanned	
Participants	Flexibility buyer	DSO	
	Flexibility service provider	Aggregator	Individual provider
	Market operator	Independent regulated	
Market scope	Negotiation time frame	Short-term	
	Flexibility need (grid level)	DSO HV	
	Offer organization	Congestion zone/s	
Market access	Prerequisites	Technical	Market
Product	Attributes (Parameters)	Standardized at UC/BC only	
	Transactional object	Energy (Activation)	
	Power	Active Power	
	Direction	Upwards	Downwards
Clearing	Matching	Continuous	
	Demand/Supply formation	One side Market	
	Grid constraint representation	Bid limitation	
	Pricing rule	Pay-as-bid	
Metering verification	Flexibility unit metering	Asset	
	Baseline method	Alternative data	
Integration	External coordination	Implements MO/s coordination	
	Existing market interaction	Defined	
Economic	Fees	Fixed	

the DSO. When congestion occurs, the DSO can request flexibility from GOPACS. FSPs then submit offers in either buy or sell orders, depending on the specific needs of the congested area. A buy order aims to reduce generation or increase consumption, while a sell order aims to increase generation or reduce consumption. The order direction will depend on the flexibility required in the area the DSO faces congestion.

In GOPACS, the bid-matching is conducted in tender mode with opening and closing times set by the DSO. While not a market, GOPACS collaborates with market operators like ETPA and the forthcoming EPEX Spot for market clearing. The system gathers all buy and sell orders, matches them, and then passes the results to the DSO. Enexis, the DSO, ultimately selects the offer with the lowest spread price. We categorize this arrangement as a one-sided market, where Enexis drives the final offer selection. The algorithm focuses solely on bid information, making *bid limitation* a key characteristic. The pricing rule is *pay-as-bid*, but with the nuance that the DSO pays only the spread. In the short-term market, the FSP gets their bid price for the offer, while in the contra-area, they receive both the market price and the spread.

In GOPACS, metering is asset-specific, as indicated by the requirement for an EAN from the FSP. The DSO, Enexis, relies on T-prognosis data for generation and consumption, which aligns with Dutch regulation — Article 5.1; par.5.1.1.1 and 5.1.1.2 [137]. Although other baselines can be agreed upon with the FSP, Enexis uses T-prognosis as its data source. Therefore, we categorize this as *alternative data*.

The integration feature of GOPACS sets it apart as it not only addresses local congestion issues but also considers the broader market impact. It coordinates with market operators and is currently integrated with ETPA, with plans to include EPEX SPOT. In terms of our taxonomy, this is classified as *market operator coordination* for external coordination and *defined* for existing market interaction. Economically, the platform operates on a subscription-based model with fixed annual fees. Currently, there are no variable fees involved.

C.2.2. Potential future design for longer negotiation time frames

In a follow-up interview, we suggest a possible market design (prescription) to help Enexis select or design a new market to complement the current GOPACS solution. Given the trend among DSOs, particularly in the UK, to incorporate long-term flexibility procurement into their network planning, our proposed market design aims to meet this need for Enexis as collected in Table C.5.

To adapt the current GOPACS system to future needs, we propose four main changes across different categories: congestion management, market scope, product, and economics.

1. Congestion Management: We recommend shifting the characteristic in the *origin* dimension from *unplanned* to *planned*. This aligns with the concept of integrating flexibility procurement into network planning, thereby allowing for better foresight and preparation.
2. Market Scope: In the *negotiation time frame* dimension, we suggest moving from a *short-term* to a *long-term* focus. This aligns with the overall shift toward more strategic, planned approaches.
3. Product: We recommend standardization for the *attributes* dimension. A nationally standardized product can streamline the market and provide guarantees, benefiting Enexis and other Dutch DSOs.
4. Economics: Regarding fees, penalties are crucial for DSOs to ensure compliance. However, they must be balanced carefully to avoid deterring participation, especially in markets dependent on network situations that vary widely in stress levels. Therefore, DSOs must find a balance that encourages FSPs to participate, even if flexibility provision is not their primary business.

C.3. Spain - OIME's local flexibility solution

OMIE is the NEMO for the Iberian Peninsula's (Spain and Portugal) day-ahead and intraday electricity markets. They are actively developing an integrated LFM solution. Although the platform is still in development and subject to changes due to evolving regulations, we have included it in our analysis based on the most recent data from October 2022. The solution's integration with other markets makes it particularly relevant to our study.

C.3.1. Business taxonomy

To condense, OMIE traditionally recognizes only day-ahead and intraday markets. However, for our analysis, we have divided their platform into four distinct market designs to capture its inherent complexities. We present these in two business taxonomies: one for their long-term and mid-term markets (Table C.6), and another for their day-ahead and intraday markets (Table C.7). This differentiation allows us to analyze OMIE's LFM in a more nuanced manner, and our taxonomies are based on available data and consultations with OMIE experts.

These four market designs differ in four critical dimensions:

1. Origin of Congestion Management: Long-term and mid-term markets focus on planned flexibility, aiding DSOs in long-term planning and DER integration. Short-term markets target unplanned, immediate congestion scenarios.

Table C.5
Potential design for long-term flexibility procurement solution.

Category	Dimension	Characteristic – Potential LFM Long-term	
CM need	Origin	Planned	
Participants	Flexibility buyer	DSO	
	Flexibility service provider	Aggregator	Individual provider
	Market operator	Independent regulated	
Market scope	Negotiation time frame	Long-term	
	Flexibility need (grid level)	DSO HV	
	Offer organization	Congestion zone/s	
Market access	Prerequisites	Technical	Market
Product	Attributes (Parameters)	Standardized at country level	
	Transactional object	Energy (Activation)	Capacity (Availability)
	Power	Active Power	
	Direction	Upwards	Downwards
Clearing	Matching	Call market (Tender)	
	Demand/Supply formation	One side Market	
	Grid constraint representation	Bid limitation	
	Pricing rule	Pay-as-bid	
Metering verification	Flexibility unit metering	Asset	
	Baseline method	Alternative data	
Integration	External coordination	Implements MO/s coordination	
	Existing market interaction	Defined	
Economic	Fees	Fixed	Variable

2. Negotiation Time Frame: The long-term market deals with years-ahead planning, the mid-term market focuses on monthly planning, the day-ahead is for next-day procurement, and the intraday market is for same-day needs, targeting isolated systems.
3. Transactional Object: Long-term and mid-term markets compensate for both energy and capacity, with an emphasis on capacity. The short-term markets only pay for the energy.
4. Market Clearing Matching: All markets except the intraday market are tender-based, initiated by the DSO's specific needs. The intraday market uses a continuous market clearing algorithm.

These designs offer DSOs a range of options to manage both planned and unplanned congestion, from long-term strategies to immediate same-day actions.

In turn, these markets share several similarities across various dimensions. These markets primarily serve the needs of DSOs in managing congestion. Participants can include both aggregators and individual providers, with OMIE acting as an independently regulated market operator. These markets focus on assets connected to a DSO's medium voltage grid, specifically those in designated congestion zones. To participate, assets must meet technical and market pre-conditions. For technical criteria, assets undergo a prequalification process, typically initiated by the DSO [62,76]. On the market side, FSPs must have a trading account on OMIE's platform and meet document requirements. We assumed that the attributes are standardized at the country level, and all markets focus on trading active power in either direction. The markets operate under a one-sided model driven by the DSO and utilize a pay-as-bid pricing mechanism for market clearing with limited bid information.

OMIE allows FSPs to offer either a collection or individual assets for metering and verification. Baselines can be historical data, forecasts, or real-time nominations from short-term markets. A distinctive feature is the integration of short-term LFMs with OMIE's existing platform, which also serves European markets in the Iberian Peninsula. Therefore, we categorized it as *MO coordination* and *defined* for existing market interaction based on [62,76]. Economically, the solution involves both fixed and variable fees. Fixed fees cover platform connectivity for DSO and FSPs, while variable fees pertain to penalties for non-fulfillment [62]. However, it is important to remark that these current designs might evolve as new regulations emerge.

Table C.6
Long-term and mid-term LFMs business taxonomy from OMIE in Spain.

Category	Dimension	Characteristic - Long-term		Characteristic - Mid-term	
CM need	Origin	Planned		Planned	
Participants	Flexibility buyer	DSO		DSO	
	Flexibility service provider	Aggregator	Individual provider	Aggregator	Individual provider
	Market operator	Independent regulated		Independent regulated	
Market scope	Negotiation time frame	Long-term		Mid-term	
	Flexibility need (grid level)	DSO MV		DSO MV	
	Offer organization	Congestion zone/s		Congestion zone/s	
Market access	Prerequisites	Technical	Market	Technical	Market
Product	Attributes (Parameters)	Standardized at country level		Standardized at country level	
	Transactional object	Energy (Activation)	Capacity (Availability)	Energy (Activation)	Capacity (Availability)
	Power	Active Power		Active Power	
	Direction	Upwards	Downwards	Upwards	Downwards
Clearing	Matching	Call market (Tender)		Call market (Tender)	
	Demand/Supply formation	One side Market		One side Market	
	Grid constraint representation	Bid limitation		Bid limitation	
	Pricing rule	Pay-as-bid		Pay-as-bid	
Metering verification	Flexibility unit metering	Portfolio	Asset	Portfolio	Asset
	Baseline method	Historical data	Alternative data	Historical data	Alternative data
Integration	External coordination	Implements NO/s coordination		Implements NO/s coordination	
	Existing market interaction	Defined		Defined	
Economic	Fees	Fixed	Variable	Fixed	Variable

Table C.7
Short-term day-ahead and intraday LFMs taxonomy from OMIE in Spain.

Category	Dimension	Characteristic - Short-term DA		Characteristic - Short-term ID	
CM need	Origin	Unplanned		Unplanned	
Participants	Flexibility buyer	DSO		DSO	
	Flexibility service provider	Aggregator	Individual provider	Aggregator	Individual provider
	Market operator	Independent regulated		Independent regulated	
Market scope	Negotiation time frame	Short-term		Real-time	
	Flexibility need (grid level)	DSO MV		DSO MV	
	Offer organization	Congestion zone/s		Congestion zone/s	
Market access	Prerequisites	Technical	Market	Technical	Market
Product	Attributes (Parameters)	Standardized at country level		Standardized at country level	
	Transactional object	Energy (Activation)		Energy (Activation)	
	Power	Active Power		Active Power	
	Direction	Upwards	Downwards	Upwards	Downwards
Clearing	Matching	Call market (Tender)		Call market (Tender)	
	Demand/Supply formation	One side Market		One side Market	
	Grid constraint representation	Bid limitation		Bid limitation	
	Pricing rule	Pay-as-bid		Pay-as-bid	
Metering verification	Flexibility unit metering	Portfolio	Asset	Portfolio	Asset
	Baseline method	Historical data	Alternative data	Historical data	Alternative data
Integration	External coordination	Implements MO coordination		Implements MO coordination	
	Existing market interaction	Defined		Defined	
Economic	Fees	Fixed	Variable		

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