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Unlocking flexibility from third-party resources: decoding the interaction between mechanisms for acquiring distribution system operator services.

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Abstract

Purpose of Review: This review explores the interaction between mechanisms for acquiring distribution system operator (DSO) services, such as network tariffs, flexible connection agreements, and local markets, considering their constitutive characteristics represented as design dimensions.

Recent Findings: Mechanisms for acquiring DSO services, such as network tariffs, flexible connection agreements, and local markets, have been recently studied in literature as a way for DSOs to access flexibility from third-party resources. However, they are typically designed as independent entities. Therefore, there is a lack of understanding regarding the interaction between these acquisition mechanisms.

Summary: This work investigates mechanisms for acquiring DSO services, especially focusing on network tariffs, flexible connection agreements, and local markets. These mechanisms, developed to facilitate the procurement of flexibility from third-party resources, are traditionally designed standalone without considering their potential synergies or incompatibilities resulting from their interaction to meet system service requirements. This paper aims to fill this gap by discussing how these mechanisms could interact with an analysis to identify possible synergies and conflicts among them by considering their design dimensions.

Keywords: Flexibility mechanism, Distribution system operator services, Network tariffs, Connection agreements, Local markets for DSO services.

Introduction

In recent years, power systems have experienced a significant transformation [1]. These systems were initially characterized by straightforward top-down functioning, generating the electricity required to fulfill immediate consumption needs. The aggregated demand was relatively predictable and could be met by a centralized generation with moderate uncertainty and capable of adjusting their production with a satisfactory level of quality [2]. However, generation primarily relied on fossil fuel facilities, which, despite their ability to provide a stable energy source, came with environmental and economic disadvantages [3]. Thus, in the evolving landscape of moving towards more sustainable energy systems, power systems must become more innovative, de-fossilized, and distributed.

The integration of renewable energy sources, such as solar and wind, at both small-scale and large-scale, introduces significant uncertainty in the power system operation due to their intermittency and variability [4,5]. The electrification of critical sectors, such as transportation, heating, and industry, has a significant impact on reducing carbon footprint and encouraging cleaner energy systems. However, it also incorporates complexities regarding infrastructure and grid capacity [5]. Moreover, the empowerment of consumers who seek increasingly active participation, driven by technological advancements and digitalization, enables them to access real-time information and make decisions regarding their energy usage [6].

In this context, power systems must become more adaptable by leveraging the potential flexibility of connected resources. This flexibility can be employed to offer system services to both transmission (TSO) and distribution (DSO) system operators and, when properly applied, could provide a cost-effective and operational alternative to traditional network reinforcement [7]. This form of flexibility adopted as an alternative to network reinforcement is widely pursued given the changing generation and demand patterns, as outlined in [7,8]. Likewise, we can highlight several initiatives that are currently being successfully implemented to solve network congestion problems. Among these are "Flexible Power" [9] in the UK, "Piclo" [10], which operates in Ireland, Italy, Portugal, the UK, and the United States, and "Nodes" [11], which operates in Norway, Sweden, and Canada.

The procurement of system services can be enabled by acquisition mechanisms, such as network tariffs, connection agreements, and local markets [12]. Although these mechanisms are currently in operation, they were designed as standalone entities. Traditionally, their original design did not consider their interaction and their combined efficiency. This paper provides detailed discussion and insights into how these acquisition mechanisms can interplay to support DSOs operations, exploring potential synergies and incompatibilities.

The remainder of the paper is structured as follows:

- Section "Flexibility for distribution system operator services" introduces the concept of flexibility in the context of DSO services, and how they can be obtained from connected resources to the electrical grid through acquisition mechanisms.
- Section "Mechanisms for acquiring DSO Services" provides a comprehensive description of network tariffs, flexible connection agreements, and local markets for DSO services. This section aims to elucidate the role of these mechanisms for acquiring DSO services, considering their constitutive characteristics in terms of design dimensions and options.
- Section "Interaction between mechanisms for DSO Services" presents the comparative analysis between the analyzed acquisition mechanisms, identifying potential synergies and conflicts via pairwise comparisons: network tariffs vs. local markets for DSO services, network tariffs vs. flexible connection agreements, and flexible connection agreements vs. local markets for DSO services.
- Section "Conclusions" provides the final remarks of the paper.

Flexibility for distribution system operator services

The concept of flexibility refers to the capability of the power system to exploit the available resources to deal with the uncertainty and variability of generation and demand, ensuring the operational boundaries and balance between electricity supply and consumption [3,13]. Leveraging this flexibility from flexible resources connected to the electrical networks allows for delaying or indefinitely deferring the network reinforcement until it becomes the most efficient solution [14]. Consequently, providing flexibility to the power system can be defined as *"the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system"* [15].

DSOs can obtain flexibility from different sources. Figure 1 illustrates a schematic for addressing potential network needs within the distribution system, developed based on [12,16]. DSOs have multiple solutions that can be applied in parallel (i.e., network reinforcement, DSO-owned flexibility resources, and mechanisms for acquiring DSO services from third parties); however, the most efficient solution from economical and technical perspectives may be found through a comprehensive examination of the capability of each solution to meet network requirements.

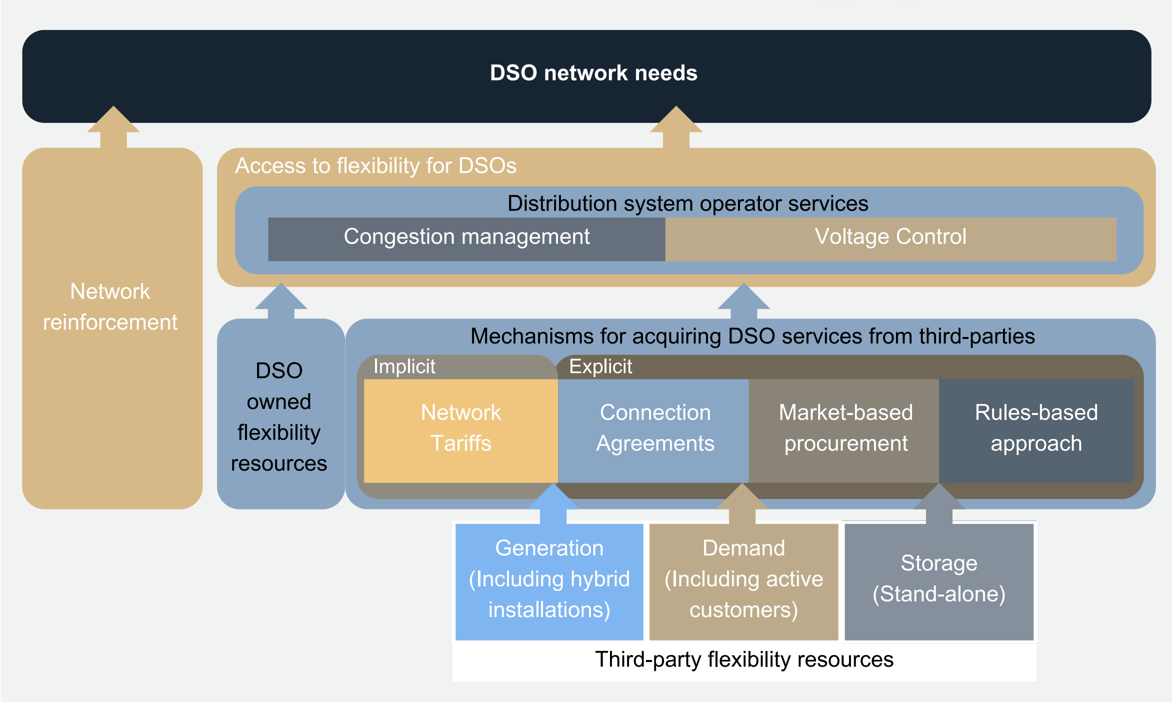


Figure 1 Mechanism for DSOs to address network needs

As shown in Figure 1, the DSO needs can be addressed traditionally by upgrading or expanding the existing electrical infrastructure to increase its capacity in response to rising demand. This process can involve the installation of new power lines, substations, or transformers, as well as the modernization of the equipment in place [17,18]. Although it can enhance the overall performance of the power supply, leading to fewer outages and increasing power quality, it can also result in higher utility bills to customers [19]. Network investment strategies can also potentially generate an oversized infrastructure, leading to economic inefficiencies. Additionally, in some instances, physical network upgrades might not be feasible due to regulatory or environmental barriers, especially in restricted areas [20]. Therefore, a favorable strategy for system operators could involve exploiting the available flexibility of the electrical grid by including accurate signals in mechanism design processes, allowing network reinforcement to be triggered only as the last available solution.

DSO can require flexibility to address network problems in the form of system operator (SO) services. In general, SO services are classified as balancing, voltage control, and congestion management [21]. As the scope of this paper is at the distribution level, the focus is on system services of congestion management and voltage control, defined as DSO services. Furthermore, although the coordination between TSOs and DSOs is relevant, the analysis of their interaction through acquisition mechanisms for system services is beyond the scope of this paper. Our primary focus is on identifying potential synergies or conflicts across acquisition mechanisms based on DSO needs. Nevertheless, it is important to acknowledge that coordination between TSOs and DSOs introduces additional complexity, which will be addressed in future research. For further insights into the challenges of ensuring efficient market coordination, please refer to [22]

The DSO services can be obtained through two approaches: by using DSO-owned flexible resources (e.g., distribution network reconfiguration, capacity banks, electronic devices) [12], or by using mechanisms for acquiring DSO services from third-parties [23,24]. Third-party flexibility resources encompass distributed generation, such as residential solar power installations, demand-side components with engaged consumers managing controllable loads, or standalone storage systems like dedicated battery facilities. The integration of advanced technologies, inherently capable of adjusting their generation or consumption patterns, offers an opportunity to locally address grid problems by shifting their network usages. In this context, appropriated mechanisms are necessary to unlock the flexibility that these third-party resources can provide to power systems as DSO services [12].

According to [16], four categories can be considered for acquiring DSO services from third-party resources: network tariffs, connection agreements, market-based procurement (bilateral contracts or markets as local markets), and a rules-based approach. These acquisition mechanisms can be employed based on how economic signals are defined and how flexibility is provided. Flexibility can be implicit or explicit [23,25,26]. The term implicit implies the absence of an explicit commitment to provide a system service. Therefore, flexible resources adjust their electrical usage patterns in response to price-based signals, such as those incorporated in network tariffs, with charge fluctuations tailored to the network requirements to encourage customers to adopt more efficient network usage. Conversely, the term explicit implies a direct acquisition through specific mechanisms that determine that flexible resources actively commit to providing system services by trading shifts in their energy profiles in market-based mechanisms, or by obligations specified in connection agreements, or rule-based mechanisms.

In the section “Mechanisms for acquiring DSO Services”, descriptions of relevant concepts of network tariffs, flexible connection agreements and local markets for DSO services are provided. Additionally, qualitative analyses aimed at identifying potential synergies or significant inefficiencies resulting from the interaction between these mechanisms are provided in the section “Interaction between mechanisms for DSO Services”.

Mechanisms for acquiring DSO Services

This section describes the mechanisms for acquiring DSO services, which are the focus of this study: network tariffs, flexible connection agreements, and local markets. It starts with an overview that outlines the objectives and design principles for each acquisition mechanism. Subsequently, the most relevant part of this section details the design dimensions and options identified for each acquisition mechanism in Table 1, Table 2, and Table 3.

The design dimensions can be understood as variables that collectively describe the nature and functionality of each mechanism, and the options denote the potential implementation values or domain for a particular dimension. The design dimensions are established according to their impact on increasing the economic efficiency of other mechanisms, as defined in the section “Interaction between mechanisms for DSO Services”. Some options within a dimension can be mutual exclusive (ME), indicating they cannot be applied at the same time. The design dimensions are categorized into meta-dimensions based on shared characteristics.

Network Tariffs concepts, design dimensions and options.

Several research studies consider that the main objective of network tariffs is to recover network costs [1,23,24,27]. Network tariffs are structured pricing mechanisms required to recuperate infrastructure investment, operation, and maintenance expenses. Additionally, they serve to bill customers for their electricity grid usage. Network tariffs can be based on the cost per unit of energy (kWh), cost per unit of capacity (kW), fixed fees, and other components (energy costs, other regulated costs, taxes, etc.) that sum up the total bill amount.

Network tariff designs should follow the regulatory principles of economic efficiency, equity and transparency [28]. But they also should be employed to send economical signals to reduce current and future network costs. These signals may impact customer behaviors, encouraging more energy-efficient practices to mitigate peak demands, thereby reducing operational costs and avoiding or delaying network reinforcement [29]. For instance, including charges with locational and temporal granularities that reflect the network conditions could incentivize customers to align their electricity consumption with periods of lower demand. Thus, network tariffs could effectively reduce grid congestion in areas with capacity limitations [28].

The literature on network tariffs is diverse, covering concepts, benefits and design principles, such as those found in [1,27–36]. Also, noteworthy insights can be explored from research project reports and publications by international organizations [24,35–37], which analyze the application of network tariffs to provide system services. Furthermore, there is a focus on modeling, primarily centered on demand response applications [38–40] and pricing methods [33,41–44] considering network tariffs.

Table 1 outlines the design dimensions and options for network tariffs. Additionally, a brief description follows.

Table 1 Design dimensions and options for network tariffs

Meta-dimension	nº	Dimension	Options					ME
Charges	1	Cost allocation methods	a) Average costs	b) Long-term incremental + Residual costs				yes
	2	Charging variable	a) Fixed	b) Used capacity (Measured)	c) Capacity (Contracted)	d) Capacity (Physical)	e) Energy	no
Locational	3	Locational granularity	a) System-wide	b) Zonal	c) Nodal			yes
Temporal	4	Temporal granularity of charges	a) Yearly	b) Seasonal (Monthly)	c) Blocks (Daily)	d) Hourly		yes

	5	Price setting periodicity	a) Year ahead (Static)	b) Day(s) ahead (Dynamic)	c) Ex-post			yes
	6	Temporal granularity of measurements	a) Yearly	b) Monthly	c) Blocks (Daily)	d) Hourly	e) Quarter hourly	yes
Assets	7	Customer differentiation	a) Technology agnostic (By voltage levels or network areas)	b) Specific tariffs according to technologies (Generation, storage, EVs., etc.)				yes
	8	Symmetry of charges (Energy or capacity components)	a) Same offtake and injection charges	b) Different offtake and injection charges				yes

The “1. Cost allocation methods” and “2. Charging variable” are categorized into the meta-dimension of “Charges” because they involve price-setting methodologies.

The “1. Cost allocation methods” depend on economic efficiency and define how the total recognized costs are allocated to consumers in alignment with the cost-causality principles [1,27,43]. Tariffs can be designed considering: a) an average cost based only on actual network costs, or b) future network costs according to the forecasted network usage. In option b), the incremental component includes the current network costs and the economic signals aimed at reducing future network investments, and the residual component is intended to recuperate the remaining costs to ensure the full recovery of total costs [29].

The “2. Charging variable” depends on cost drivers [28]: a) fixed charges provide stability but lack incentives for customer behavior changes. The capacity charge can be established based on b) measuring the maximum peak demand being ex-posts, c) a predetermined value in the connection contract, with penalties if exceeded, d) the availability of physical installation at each connection point. Furthermore, e) the energy charge could provide signals to adjust consumption patterns when it incorporates temporal granularity, such as pricing differentiation based on time of use.

The “3. Locational granularity”, classified under the meta-dimension of “Locational”, refers to how a location is partitioned to allocate network charges. Network tariffs can be assigned [35,43]: a) uniformly system-wide, b) differentiated by zones, or c) based on connection points. Tailoring location-specific signals can reflect spatial cost variations and capacity constraints across the grid, impacted by factors such as user density, distance from generation sources, and operational boundaries of components. Network tariffs with low granularity lead to greater socialization of network costs around a jurisdiction, resulting in customers in areas with lower network costs to cross-subsidize those in higher network cost areas [28]. A greater locational granularity allows better cost reflectiveness, which is also especially important due to the rise of distributed resources. However, network tariffs that are too spatially granular could lead to higher implementation costs without guaranteeing that customers adequately respond to the pricing signals to reduce network costs.

The meta-dimension of “Temporal” groups to “4. Temporal granularity of charges”, “5. Price setting periodicity”, and “6. Temporal granularity of measurement”.

The “4. Temporal granularity of charges” refers to how time is partitioned to allocate network charges. It can be [29,39,43]: a) flat throughout the year, b) varying between seasons, c) subdivided into specific time blocks, such as hourly segments within a day, or d) defined by finer intervals, such as hourly or less. A higher temporal granularity more accurately reflects changes in demand and generation costs, allowing for a closer alignment with actual usage patterns. Still, too much temporal granularity can introduce unnecessary complexities into the billing process and make it more difficult for consumers to respond to price signals [28].

The “5. Price setting periodicity” determines the interval for recalculating network charges. Charges should be adjusted according to deviations of actual peak demands from forecasted values. It can be established [28]: a) static considering the year ahead, b) more granular, considering day(s) ahead, or c) ex-post after the network usage is known.

The “6. Temporal granularity of measurement” involves time intervals for data collection, utilizing suitable devices such as smart meters. It can be a measure of every [35]: a) year, b) month, c) by blocks within the same day, d) hour, or e) quarter-hourly. The “4. Temporal granularity of charges” should be at least equal to or greater than the “6. Temporal granularity of measurements”.

Lastly, “7. Customer differentiation” and the “8. Symmetry of charges (Energy or capacity components)” can be categorized under the meta-dimension of “Assets”.

The “7. Customer differentiation” offers the possibility to tailor specific tariff charges based on [28,35]: a) voltage levels or specific network areas, being technologic agnostic, or b) specific according to certain technologies. Although option b) remains relatively common in practice, they may negatively impact allocative equity and technology-neutral principles, which require no differentiation of network charges across diverse customer segments [36].

The “8. Symmetry of charges (Energy or capacity components)” considers whether network charges can be [27]: a) symmetric for energy withdrawals and injections, i.e., the same charge but with the opposite sign, or b) asymmetric, if energy withdrawals and injections can have different network charges.

Connection agreement concepts, design dimensions and options.

Traditionally, network customers have been assured to provide firm grid access to their contracted capacity via connection agreements. However, as the dynamics of power systems evolve, increasing congestion risks and associated costs, the guarantee of these firm connections is becoming less certain. In the EU, there is a growing trend towards adopting alternative connection agreements as a means to enhance flexibility, accompanied by several regulatory challenges [24].

Alternative connection agreements, also known as flexible connection agreements or non-firm connection agreements, can be considered a deviation from traditional firm rights. They can allow new customers to access the grid while waiting for network reinforcement until it becomes viable, for example, when there are enough customers to socialize the required costs. These agreements, temporary or permanent, may either restrict the time periods allowed for injecting or withdrawing energy, or restrict the capacity that can be exported or imported, particularly in areas with limited network hosting capacity [45]. Consequently, system operators could no longer guarantee energy exchange at total capacity at all times, allowing for interruptions or curtailments under specific conditions, such as managing congestion problems or balancing the generation and demand. Therefore, service operators can agree with customers to make alternative connection agreements in return for cheaper connection fees [46].

The current literature on connection agreements offers a comprehensive exploration of fundamental concepts, benefits, and design principles [20,47–50]. This exploration provides an understanding of the strategic significance of these agreements in ensuring grid connections to future customers according to the network conditions. Additionally, significant insights can also be gathered from research project reports and publications by international organizations [25,45,51]. These contributions offer practical insights into the implication of these acquisition mechanisms in addressing challenges in contemporary electrical networks.

Following the current discussion, Table 2 outlines the design dimensions and options for flexible connection agreements with a description provided below.

Table 2 Design dimensions and options for flexible connection agreements

Meta-dimension		nº	Dimension	Options				ME
Product	Temporal	1	Duration of flexible connection	a) Temporary	b) Permanent			yes
		2	Curtailment notification	a) Day-ahead	b) Intra-day	c) Real-time	d) Ex-post	yes
		3	Connection costs	a) Deep connection costs	b) Shallow connection costs			yes
		4	Benefit of the DSO allowing flexible connection	a) Avoid reinforcement (Network expansion is not possible)	b) Defer reinforcement (More economic than network expansion)	c) Preliminary connection (Network expansion is committed in a future year)		no
		5	Network connection criteria	a) Capacity limitation	b) Voltage level limitation	c) Other security criteria (N, N-1)	d) Short-circuit power rate	no
		6	Activation of the energy curtailment due to flexible connection	a) Emergency (Grid failure risk)	b) Maintenance	c) Congestion		no
		7	Pre-definition of curtailment	a) Peak/off-peak	b) Seasonality (Days or periods)			yes
		8	Principle of access	a) Pro-rata	b) Last input first output (LIFO)	c) Auction	d) Curtailment proportional to level of congestion created	yes
		9	Compensation payments for energy curtailment	a) Fixed	b) Set by the local flexibility market where	c) Local market-indexed where the	d) None	yes

					the flexible connection is participating as price taker	flexible connection is bidding a free price		
		10	Possibility to sell the expected curtailed energy	a) Bilateral contracts		b) Local markets		yes
		11	Maximum curtailment	a) Duration (Hours)	b) Capacity limitation	c) Energy limitation	d) Monetary limitation	no
Assets		12	Eligible customers	a) Generation (Including hybrid installations)	b) Demand (Including active customers)	c) Storage (Stand-alone)		yes

Considering the characteristics of the connection agreement mechanism, three meta-dimensions are identified. The first eleven are product-oriented, therefore, they are categorized under the meta-dimension of “Product”. However, the design dimensions “1. Duration of flexible connection” and “2. Curtailment notifications” incorporate temporal components, consequently, they are also categorized under the meta-dimension of “Temporal”. The dimension of “12. Eligible customers” is categorized under the meta-dimension of “Assets”.

The “1. Duration of flexible connection” can be [45,50]: a) temporary, for example, granted until more customers require access in a particular connection point and the cost of the necessary network reinforcement can be socialized, or the network reinforcement is triggered since the most efficient solution. Additionally, it can be b) permanent flexible connection contracts when network expansion is not possible at all or extremely costly, such as in protected areas.

The “2. Curtailment notification” specifies the time in advance to notify customers when curtailment is expected to occur. This factor is crucial to customers because they can make informed decisions about their operations. The notification can be made in several timeframes according to the network requirements, such as [49]: a) one day prior, b) hours in advance on the same day, c) near to real-time, d) post-outage to address unforeseen events.

The “3. Connection costs” refers to the costs for network reinforcement that should be recovered for allocating new customers or those who want to increase their current capacity in areas with hosting capacity limitations [35,52]. It can be determined whether: a) network reinforcement is necessary to accommodate the increased demand from upgraded capacity, or b) new customers can connect without incurring additional charges and only need to pay for their own installation grid.

The “4. Benefit of the DSO allowing flexible connection” encompasses the purpose of opting for flexible connection as an alternative. Non-firm grid access permits DSOs [49]: a) to avoid network expansion when it is unfeasible, for example, in restricted areas, b) deferred network upgrades, e.g., while awaiting an increase in the number of connected customers to socialize the required costs, or c) it can provide an interim solution for connection-seekers to access the grid until the network capacity is upgraded.

The “5. Network connection criteria” includes grid requirements to consider flexible connection agreements when DSOs are evaluating mechanisms for procuring flexibility [49]. For instance, flexible connections can be required when DSOs face challenges related to: a) available capacity in a particular connection point, b) voltage level restrictions, c) security concerns like N, N-1 criteria, or d) short-circuit power ratings may not be met.

The “6. Activation of the energy curtailment due to flexible connection” refers to the specific reason prompting the order to activate the flexible connection [49,53]. This requirement may arise: a) in cases of failure risk, in which customers could be curtailed if problems within the network could increase imbalances, b) where there are network limitations due to the need to perform regular maintenance in specific areas, or c) when congestion-based curtailment can be activated where there is excess energy flow, especially in abundant renewable energy production periods, and it cannot be aligned with consumption needs.

The “7. Pre-definition of curtailment” allows for the knowledge of potential curtailment hours in compliance with the transparency principle and should be clearly stated in the connection contract [49]: a) when congestions arise from demand fluctuations, it can be applied specific capacities for peak and off-peak periods, or b) when it may be adapted to the seasonality of resource availability, encompassing specific days or timeframes.

The “8. Principle of access” outlines curtailment strategies for customers [20,49]: a) “Pro-rata” distributes curtailment equally across all customers, favoring new customers but adding uncertainty about future curtailment levels for existing customers. b) “Last In First Out (LIFO)” ensures that newer customers face curtailment first, offering predictability to existing customers at the expense of higher risk for new customers. d) In “auction,” the access is considered according to which customers are most willing to accept the highest curtailment. Or e) prioritizing curtailment based on each customer contribution to “congestion”, the customer contributing most significantly to congestion is curtailed first.

The “9. Compensation payments for energy curtailment” provide economic certainty for customers and should be clearly specified in the connection contract. It can be structured as: a) a fixed amount, b) set by the local market where the flexible connection is participating as a price taker, c) considering a variable payment according to a local market where the flexible connection is bidding a free price, or c) with no assigned payments.

The “10. Possibility to sell the expected curtailed energy” addresses how customers can trade their energy that would otherwise be curtailed due to upstream congestions [49]. It can be structured: a) through direct negotiation through bilateral contracts, or b) involve local flexibility markets.

The “11. Maximum curtailment” defines the total allowable requirement for curtailment defined in the connection contract. It can be based on: a) the maximum annual curtailment duration, b) considering the maximum capacity that can be curtailed, c) limiting the energy that can be curtailed annually, or d) due to the introduction of monetary limitations.

Finally, “12. Eligible customers for flexible connections” varies based on the network state [45], accommodating different technologies, including: a) generation facilities, b) active demand-side consumers, or c) stand-alone storage.

Local markets for DSO services concepts, design dimensions, and options.

This section delves into market-based mechanisms for acquiring DSO services, with a focus on those designed to provide flexibility to the electrical grid in concordance with specific area requirements. Commonly referred to as local markets (LMs) for system services or local flexibility markets. LMs are a solution for effectively integrating local DERs to address local challenges of grid management [16,54].

As defined by [21], a LM for SO services constitutes a market where service providers offer products for local system operator services. Therefore, it implies that flexibility buyers and sellers participate in the market processes like contracting, activation, and settlement [55]. These markets serve as a platform for acquiring flexibility through long-term and short-term mechanisms customized to specific network requirements [23]. The efficiency of this model is predicated on the liquidity of markets, the cost-effectiveness compared to alternative solutions, and the capacity to mitigate market distortions [56]. These markets may be managed either by system operators or by a neutral third party provided such arrangements [21].

The extensive literature that delves into concepts, benefits and design principles of LMs for DSO services, mentioned in references [55,57–61] is complemented by significant insights from research project reports [62–71] and publications by international organizations [10,11]. There is a significant emphasis on modeling, particularly focusing on DSO-owned flexibility resources [72,73] and LMs for DSO services with multiple service providers modeling [74–76].

Table 3 details the design dimensions and options for local markets for DSO services, accompanied by an explanation provided below.

Table 3 Design dimensions and options for local markets for DSO services

Meta-dimension	nº	Dimension	Options					ME
Locational	1	Flexibility need grid level	a) High voltage	b) Medium voltage	c) Low voltage			yes
Product Temporal	2	Negotiation time frame (Gate opening and closure for participation)	a) Long-term (Weeks-ahead to years-ahead)	b) Short-term (Real-time, intraday, day-ahead)				yes
	3	Contract length	a) Yearly	b) Monthly	c) Weekly	d) Daily	e) Hourly	yes
	4	Temporal bid granularity	a) > 1 hour	b) 1 hour	c) 30 min	d) 15 min		yes
	5	Response time (Activation)	a) > 1 hour	b) 30 min – 1 hour	c) 15 min – 30 min	d) < 15 min		yes

		6	Transactional object	a) Energy (Activation)	b) Capacity (Availability)		no
		7	Power	a) Active power	b) Reactive power		no
		8	Direction	a) Upwards	b) Downwards		no
		9	Symmetry requirements (For upwards and downwards)	a) Symmetric products	b) Asymmetric products		yes
Assets		10	Source (Flexibility assets)	a) Generation (Including hybrid installations)	b) Demand (Including active customers)	c) Storage (Stand-alone)	yes

The “1. Flexibility needs grid-level” due to its spatial characteristics are considered within the “Locational” meta-dimensions. It specifies the voltage level within the electricity grid where local flexibility services are required [77,78]. Flexible resources located as close as possible to the congestion point, for example, in the same feeder, could have a greater impact from a technical perspective [23]. System services can be essential across various levels of the electricity grid: a) at high voltage for managing power flows in generation and transmission, b) at medium voltage in sub-transmission or distribution substations for maintaining voltage and frequency within operational boundaries, or c) at low voltage in distribution networks serving end-users with demand-side management and distributed energy resources integration.

The “2. Negotiation time frame”, “3. Contract length”, “4. Temporal bid granularity” and “5. Response time (Activation)” incorporate temporal components, categorizing them in the meta-dimension of “Temporal”. Furthermore, “4. Temporal bid granularity” and “5. Response time (Activation)” encompass product-related characteristics alongside the design dimensions of the transactional object, power, direction and symmetry requirements, which are under the meta-dimensions of “Product”.

The “2. Negotiation timeframe” outlines the period for planning and submitting bids in LM for DSO services [77]. This period starts with the gate opening, where the service requirements are released to service providers, and the gate closure marks the end of this negotiation phase, in which the clearing process aligns DSO service offers with network needs. This timeframe varies: a) extending from weeks to years ahead for long-term planning of services, or b) encompass shorter durations like real-time, intra-day, or day-ahead markets for immediate grid operational requirements.

The “3. Contract length” establishes the duration of a DSO service contract, with a commitment from the flexible resource to remain available [78]. These timeframes are selected to align with the specific requirements of the network and the capabilities of system service providers, covering both long-term and short-term objectives. Options for contract duration include: a) yearly, b) monthly, c) weekly, d) daily, or e) hourly periods.

The “4. Temporal bid granularity” determines the temporal resolution or the smallest time interval for adjusting system services to ensure continuous response to network requirements [77]. Available granularities could include: a) intervals greater than one hour, b) providing bids hourly or longer time blocks, c) one-hour intervals, d) 30-minute intervals, or e) quarter-hourly intervals. These options enable participants to address a wide range of scenarios, allowing them to tailor their bidding strategies to meet specific needs and network conditions. The measurement equipment employed must possess the capability to measure at least the same level of granularity.

The “5. Response time (Activation)” defines the time period for a flexible resource to adjust its output following a command signal, whether it involves an increase (ramp-up) or a decrease (ramp-down) in power or energy. Resources can be categorized based on their activation speed, including those with: a) slower responses exceeding one hour, b) with moderate responses ranging from 30 minutes to one hour, or d) responding within 15 to 30 minutes, and those with nearly instantaneous response time of less than 15 minutes.

The “6. Transactional object” refers to a type of service required from the LM for system services [77]. It can: a) be a commitment of the flexible resources to be available in the form of standby capacity, which emphasizes the capability of the resource to remain in reserve but be prepared to mobilize energy if needed, or b) include the active use of these resources for real-time responses, encompassing the injection or absorption of energy to address fluctuations in demand or generation while mitigating network disturbances.

The “7. Power” corresponds to the specific type of power required to address network problems [77,79]: a) when congestion issues arise in power lines or transformers, active power is needed due to the direct impact on the operational boundaries of these components, or b) concerning bus problems, such as overvoltage or undervoltage, reactive power may be required to handle voltage fluctuations and support the operation of reactive components connected to the grid. European projects such as EUniversal [64] and CoordiNet [66] are exploring the utilization of active and reactive power for congestion management and voltage control purposes.

The “8. Direction” identifies the direction in which capacity or energy flows are required [91]: a) when upward activation is needed, they can be provided by increasing generation or reducing consumption, or b) when downward activation is needed, they can be provided by decreasing generation or increasing consumption.

The “9. Symmetry (For upwards and downwards)” requirements for upwards and downwards are focused on the solution type provided. Solutions can be [91]: a) symmetric, addressing both upward and downward needs equally, or b) asymmetric, tailored to specific network requirements.

Finally, the dimension of “10. Source” is categorized under the meta-dimension of “Assets”. It corresponds to the specific flexible resource employed to provide the system services required [80]. It can encompass a variety of assets, including: a) power generation sources, such as renewable energy installations and hybrid power plants, capable of adjusting their output to meet network needs, b) using demand-side management methods and active customer participation, allowing customers to adapt their electricity patterns, or c) considering stand-alone energy storage systems such as batteries, which can store excess energy during periods of surplus and release it when needed.

Interaction between mechanisms for DSO Services

Despite the benefits of the mechanisms for acquiring DSO services like network tariffs, flexible connection agreements, and local markets, their stand-alone design overlooks the potential synergies that could be achieved and which could support relieving the challenges of the electrical networks due to the energy transition.

Recent literature, such as [81], suggests a framework for categorizing congestion management mechanisms that include smart tariffs, local markets, and direct control methods. Additionally, the research outlined in [14] introduces a decision-making framework for choosing among common market-based and non-market-based approaches. Moreover, [23] proposes a contextual analysis aimed at integrating several mechanisms to reach the demands for flexibility and grid services. Additionally, [82] proposes a methodology for congestion management using local flexibility markets and variable connection capacity.

Regardless of prior research, there remains an evident gap in understanding the interplay between the acquisition mechanisms. Therefore, this work seeks to bridge these gaps through an examination of their design characteristics. The design dimensions and options defined in the section "Mechanisms for acquiring DSO Services", which collectively describe the different mechanisms for acquiring DSO services, are employed to conduct comparative analyses aimed at identifying potential interaction among the mechanisms. These analyses entail the pairwise comparison of the mechanisms on an options basis, defined in the current analysis as cross-options, and also considering the high-level meta-dimensions since mechanisms may exhibit potential for interaction if their respective design dimensions are categorized similarly (e.g., temporal, spatial, product-related design dimensions). The essential criterion for evaluating the interplay of cross-options lies in the expected impact on economic efficiency as a result of their combined application. The economic efficiency principle can be considered as the optimal allocation of resources to maximize global welfare [1]. In the current research, it has been considered that the absence of conflict among cross-options enhances economic efficiency. In contrast, conflicts between mechanism interactions detract from the principle of economic efficiency. Based on this, four possible conditions for each cross-option have been determined:

- Cross-options labeled as green indicate that both mechanisms can be applied simultaneously without apparent loss of economic efficiency.
- Cross-options labeled as red could indicate that both cross-options cannot be simultaneously applied due to misalignments. Such misalignments may come from physical units of measurement or granularity discrepancies that can create potential infeasibilities. Also, it could indicate situations of double charging or double rewarding, the uneven playing field for network users, and market power issues that could create potential inefficiencies from the coexistence of the two mechanisms.
- Cross-options labeled as orange indicate that both mechanisms may determine loss of economic efficiency to be analyzed considering the context's condition.
- Cross-option in grey refers that the interaction is irrelevant or not applicable.

The results of this pairwise comparison analyses of the acquisition mechanisms are presented for:

- Network tariffs vs. local markets for DSO services in Table 4, as well as the respective descriptions in able 5.

- Network tariffs vs. flexible connection agreements in Table 6, as well as the respective descriptions in Table 7.
- Flexible connection agreements vs. local markets for DSO services in Table 8, as well as the respective descriptions in Table 9.

Comparative analysis between network tariffs vs. local market for DSO services

Table 4 Pairwise comparison in terms of design dimensions between network tariffs and local market for DSO services

			Network tariffs	Charges							Locational			Temporal												Assets			
				Cost allocation methods		Charging variable					Locational granularity			Temporal granularity of charges				Price setting periodicity			Temporal granularity of measurements					Customer differentiation		Symmetry of charges	
			Local markets for DSO services	Average costs	Long-term incremental +Residual costs	Fixed	Used capacity (Measured)	Capacity (Contracted)	Capacity (Physical)	Energy	System-wide	Zonal	Nodal	Yearly	Seasonal (Monthly)	Blocks (Daily)	Hourly	Year ahead (Static)	Day(s) ahead (Dynamic)	Ex-post	Yearly	Monthly	Blocks (Daily)	Hourly	Quarter hourly	Technology agnostic	According to technologies	Same offtake and injection	Different offtake and injection
	Locational	Flexibility need grid level	High voltage								🟩	🟧	🟧																
			Medium voltage							1	🟩	🟩	🟧																
			Low voltage								🟩	🟩	🟩				i			ii					iii				
	Temporal	Negotation time frame	Long-term											🟧	🟧	🟧	🟧	🟩	🟩	🟧	🟩	🟩	🟩	🟩	🟩				
			Short-term											🟩	🟩	🟧	🟧	🟩	🟩	🟧	🟩	🟩	🟩	🟩	🟩				
		Contract Length	Yearly											🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟥	🟩	🟩	🟩	🟩				
			Monthly											🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟥	🟥	🟩	🟩	🟩				
			Weekly											🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟥	🟥	🟥	🟩	🟩				
			Daily											🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟥	🟥	🟥	🟩	🟩				
			Hourly										2	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟥	🟥	🟥	🟩	🟩				
Product		Temporal bid granularity	>1 h											🟧	🟧	🟧	🟧	🟩	🟩	🟧	🟥	🟥	🟧	🟩	🟩				
			1 hour											🟧	🟧	🟧	🟧	🟩	🟩	🟧	🟥	🟥	🟥	🟩	🟩				
			30 min											🟧	🟧	🟧	🟧	🟩	🟩	🟧	🟥	🟥	🟥	🟥	🟩				
			15 min											🟧	🟧	🟧	🟧	🟩	🟩	🟧	🟥	🟥	🟥	🟥	🟩				
		Response time (Activation)	>1 hour											🟧	🟧	🟧	🟧	🟩	🟩	🟧	🟥	🟥	🟧	🟩	🟩				
			30 min - 1 hour											🟧	🟧	🟧	🟧	🟩	🟩	🟧	🟥	🟥	🟥	🟩	🟩				
			15 min - 30 min	3										🟧	🟧	🟧	🟧	🟩	🟩	🟧	🟥	🟥	🟥	🟥	🟩				
			< 15 min											🟧	🟧	🟧	🟧	🟩	🟩	🟧	🟥	🟥	🟥	🟥	🟩				
		Transactional object	Energy (Activation)	🟧	🟧	🟩	🟧	🟧	🟧	🟧																			
			Capacity (Availability)	🟧	🟧	🟩	🟧	🟧	🟧	🟧																			
		Power	Active power	🟧	🟧	🟩	🟧	🟧	🟧	🟧																			
			Reactive power	🟧	🟧	🟩	🟩	🟩	🟩	🟩																4			
		Direction	Upwards																							🟧	🟧	🟧	🟧
			Downwards																							🟧	🟧	🟧	🟧
		Symmetry requirements	Symmetric products																							🟧	🟧	🟧	🟧
			Asymmetric products																							🟧	🟧	🟧	🟧
	Assets	Source (Flexibility assets)	Generation																							🟩	🟧	🟧	🟩
			Demand																							🟩	🟧	🟧	🟩
			Storage																							🟩	🟧	🟧	🟩

Colour-code	Description
🟩	There is no loss of economic efficiency resulting from their interaction
🟧	Misalignments or inefficiencies that reduce economic efficiency due to their interaction
🟥	Potential loss of economic efficiency but requires an analysis of the context condition
⬜	Interaction is irrelevant or not applicable

able 5 Description of the comparative analysis between network tariffs and local markets for DSO services

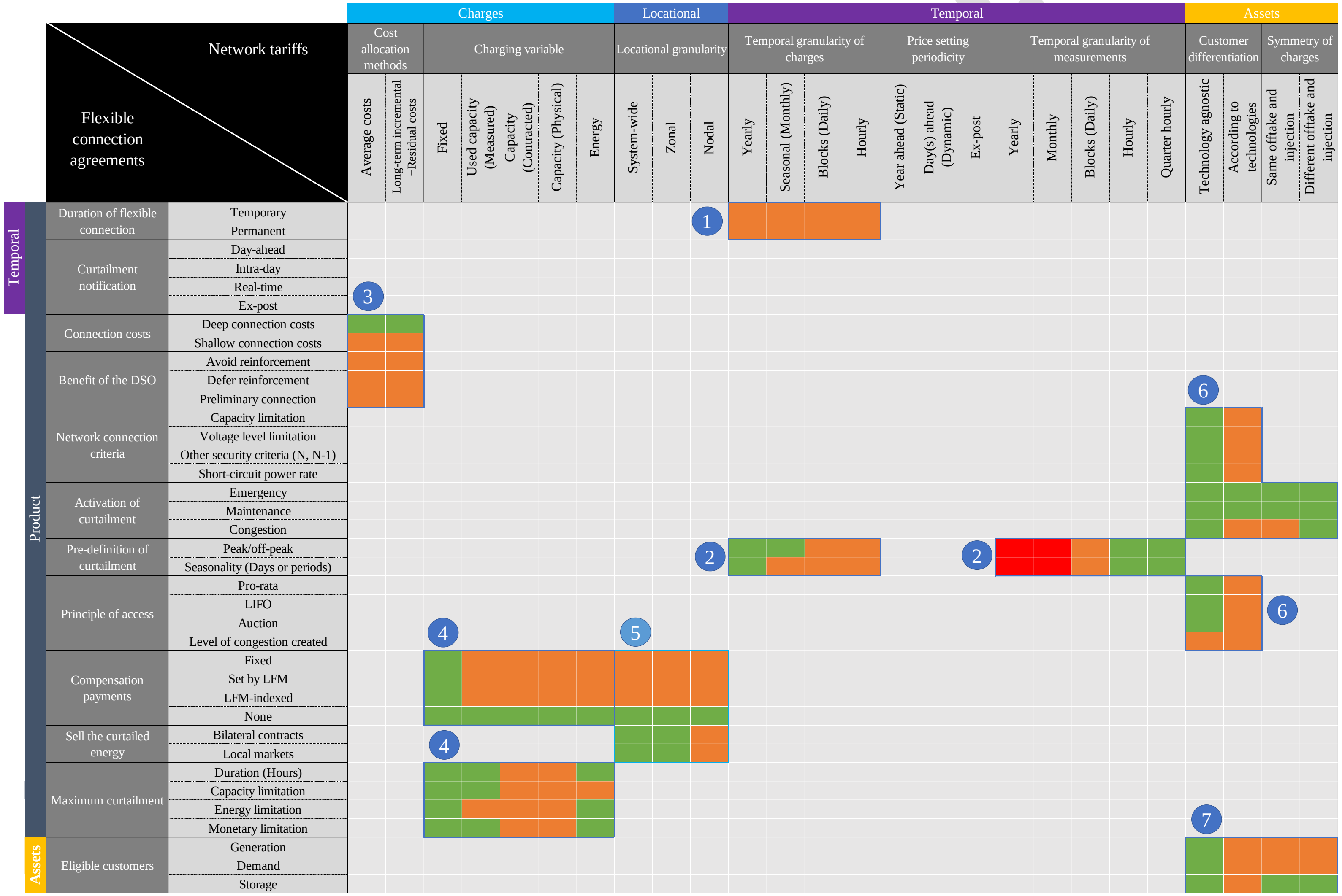
Network Tariffs			Comparative Analysis	Local Market for DSO services		
Meta dim	**Dimension**	**Options**		**Options**	**Dimension**	**Meta dim**
Locational	Locational granularity	System-wide Zonal Nodal	Group ①: Network tariffs with a lack of granularity cannot accurately reflect network costs and can fail to incentivize customer-efficient behaviors. In such cases, LM for DSO services can leverage local flexibility from distributed resources to solve local network problems, reducing operational costs or mitigating future investment requirements in specific areas (block in green). On the other hand, when local markets for DSO services are utilized to address network problems, but the network tariffs already include locational granularity charges that overlap, customers can be double signaled by both mechanisms, distorting their combined efficiency. These scenarios require a more specific analysis (blocks in orange).	High voltage Medium voltage Low voltage	Flexibility needs grid level	Locational
Temporal	Temporal granularity of charges	Yearly Seasonal (Monthly) Blocks (Daily) Hourly	Group ② ⓘ: If the duration of the "Negotiation time frame" extends beyond the duration of the "Temporal granularity of charges", it may result in cost alignment challenges. Ideally, network tariff charges may be internalized by the customers in their offers to participate in a local DSO service market. If these costs shift during the negotiation periods, it could affect or benefit customer offers, reducing their combined efficiency. Thus, this condition requires a more detailed analysis (blocks in orange). The "Temporal granularity of charges" and "Contract length" can be applied simultaneously without causing conflicts between both mechanisms (blocks in green). On the other hand, the interactions of "Temporal granularity of charges" with "Temporal bid granularity" and "Response time" require a more detailed examination according to the context (blocks in orange). LM for DSO services could complement network tariffs in those cases where the "Temporal bid granularity" and "Response time" are restricted by "The temporal granularity of charges". For instance, if the temporal granularity of network charges is by "Blocks	Long-term Short-term	Negotiation time frame	Temporal
	Price setting periodicity	Year ahead (static) Day(s) ahead (dynamic)		Yearly Monthly Weekly Daily Hourly	Contract Length	

	Ex-post	(daily)", LM for DSO services with time granularity longer than one hour could improve the economic efficiency of the signal sent to customers. On the other hand, if LM for DSO services with more than an hour differentiation, for example, with a larger duration compared to a block duration, customers have to average the effect of tariffs potentially creating inefficient price signals. Moreover, if network tariffs already include temporal granularity charges and local markets for DSO services are employed, customers could receive double signals.	>1 h 1 hour 30 min 15 min	Temporal bid granularity
Temporal granularity of measurements	Yearly Monthly Blocks (Daily) Hourly Quarter hourly	Group ② ⅱ : In scenarios with annual price-setting periodicity, customers are informed one year in advance about the network charges they incur for each time period of the year, but forecasted peak hours may not be aligned with actual peak demand periods. Thus, a LM for DSO services activated on day-ahead basis could predict the actual network peak periods more accurately. On the other hand, a network tariff with an ex-post price setting already includes signals for solving network problems. If ex-post charges are applied, local markets for DSO services should be carefully designed to avoid double signals to customers (blocks in orange). In scenarios where network tariff designs are restricted by temporal granularities, local markets for DSO services serve as a complementary mechanism, enhancing the capability of the flexible resources to meet specific network requirements and increasing their combined efficiency (blocks in green). Group ② ⅲ : The measurement equipment capabilities, such as electricity meters, restrict the granularity of other design dimensions. When the design dimensions of "Contract length", "Temporal bid granularity" and "Response time" in LM for DSO services are greater than the "Temporal granularity of measurement" in network tariff, potential combinatorial infeasibilities appear due to technical misalignments between operational requirements and measurement precision (blocks in red). When the granularities of these design dimensions are close, it is necessary to examine the specific contexts (blocks in orange). For instance, if the duration of "Temporal bid granularity" or the "Response time" exceeds the duration of the option of blocks (daily) in the "Temporal granularity of the measurement", it leads to issues in capturing accurate measurements due to the mismatch in temporal resolutions.	>1 hour 30 min - 1 hour 15 min - 30 min < 15 min	Response time (Activation)

<table>
<tr>
<td rowspan="3">Charges</td>
<td>Cost allocation methods</td>
<td>Average costs
Long-term incremental+ Residual costs</td>
<td rowspan="3">Group ③:
When charges lack granularity, they may not accurately reflect the wide range of costs and usage patterns across different customers, locations, or time periods, then LM for DSO services could fill these gaps. Conversely, when charges become too granular, both for network tariff and LM for DSO services, there is a risk of overlap between the signals sent by both mechanisms, charging or rewarding customers twice for the same service or resource usage. These conditions require a more nuanced analysis to better understand the situation (blocks in orange). When the “Charging variable” in network tariffs are based on a flat rate, LM for DSO services potentially may introduce long-term cost signals. Moreover, since network tariffs are restricted to incorporate signals for reactive power provision, LM for DSO services could effectively address these deficiencies (blocks in green).</td>
<td rowspan="2">Capacity (Availability)
Energy (Activation)</td>
<td rowspan="2">Transactional object</td>
<td rowspan="6">Product</td>
</tr>
<tr>
<td rowspan="2">Charging variable</td>
<td rowspan="2">Fixed
Used capacity (Measured)
Capacity (Contracted)
Capacity (Physical)
Energy</td>
</tr>
<tr>
<td>Active power
Reactive power</td>
<td>Power</td>
</tr>
<tr>
<td rowspan="4">Assets</td>
<td rowspan="2">Customer differentiation</td>
<td rowspan="2">Technology agnostic
According to technologies</td>
<td rowspan="4">Group ④:
Following the principles of cost reflectivity and equity, network tariffs should be designed to remain as technology-neutral as possible (EVs, storage systems, rooftop PV systems). This ensures that network tariffs do not disadvantage network customers with less access to advanced technologies, creating an uneven playing field. Additionally, if withdrawal and injection charges are not symmetrical it might unfairly benefit certain types of technologies. Thus, a detailed examination of these cases (blocks in orange) is essential to avoid biased outcomes.</td>
<td>Upwards
Downwards</td>
<td>Direction</td>
</tr>
<tr>
<td rowspan="2">Symmetric products
Asymmetric products</td>
<td rowspan="2">Symmetry requirements</td>
</tr>
<tr>
<td rowspan="2">Symmetry of charges</td>
<td rowspan="2">Same offtake and injection
Different offtake and injection</td>
</tr>
<tr>
<td>Generation
Demand
Storage</td>
<td>Source (Flexibility assets)</td>
<td>Assets</td>
</tr>
</table>

Comparative analysis between network tariffs vs. connection agreements

Table 6 Pairwise comparison in terms of design dimensions between network tariffs and flexible connection agreements



			Charges							Locational			Temporal												Assets			
		Network tariffs	Cost allocation methods		Charging variable					Locational granularity			Temporal granularity of charges				Price setting periodicity			Temporal granularity of measurements					Customer differentiation		Symmetry of charges	
		Flexible connection agreements	Average costs	Long-term incremental +Residual costs	Fixed	Used capacity (Measured)	Capacity (Contracted)	Capacity (Physical)	Energy	System-wide	Zonal	Nodal	Yearly	Seasonal (Monthly)	Blocks (Daily)	Hourly	Year ahead (Static)	Day(s) ahead (Dynamic)	Ex-post	Yearly	Monthly	Blocks (Daily)	Hourly	Quarter hourly	Technology agnostic	According to technologies	Same offtake and injection	Different offtake and injection
Temporal	Duration of flexible connection	Temporary										①	🟧	🟧	🟧	🟧												
		Permanent											🟧	🟧	🟧	🟧												
	Curtailment notification	Day-ahead																										
		Intra-day																										
		Real-time	③																									
		Ex-post																										
Product	Connection costs	Deep connection costs	🟩	🟩																								
		Shallow connection costs	🟧	🟧																								
	Benefit of the DSO	Avoid reinforcement	🟧	🟧																								
		Defer reinforcement	🟧	🟧																								
		Preliminary connection	🟧	🟧																					⑥			
	Network connection criteria	Capacity limitation																							🟩	🟧		
		Voltage level limitation																							🟩	🟧		
		Other security criteria (N, N-1)																							🟩	🟧		
		Short-circuit power rate																							🟩	🟧		
	Activation of curtailment	Emergency																							🟩	🟩	🟩	🟩
		Maintenance																							🟩	🟩	🟩	🟩
		Congestion																							🟩	🟧	🟧	🟩
	Pre-definition of curtailment	Peak/off-peak										②	🟩	🟩	🟧	🟧			②	🟥	🟥	🟧	🟩	🟩				
		Seasonality (Days or periods)											🟩	🟧	🟧	🟧				🟥	🟥	🟧	🟩	🟩				
	Principle of access	Pro-rata																							🟩	🟧		
		LIFO																							🟩	🟧	⑥	
		Auction																							🟩	🟧		
		Level of congestion created			④					⑤															🟧	🟧		
	Compensation payments	Fixed			🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟧																
		Set by LFM			🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟧																
		LFM-indexed			🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟧																
		None			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																
	Sell the curtailed energy	Bilateral contracts								🟩	🟩	🟧																
		Local markets			④					🟩	🟩	🟧																
	Maximum curtailment	Duration (Hours)			🟩	🟩	🟧	🟧	🟩																			
		Capacity limitation			🟩	🟩	🟧	🟧	🟧																			
		Energy limitation			🟩	🟧	🟧	🟧	🟩																			
		Monetary limitation			🟩	🟩	🟧	🟧	🟩																⑦			
Assets	Eligible customers	Generation																							🟩	🟧	🟧	🟧
		Demand																							🟩	🟧	🟧	🟧
		Storage																							🟩	🟧	🟩	🟩

Colour-code	Description
🟩	There is no loss of economic efficiency resulting from their interaction
🟧	Misalignments or inefficiencies that reduce economic efficiency due to their interaction
🟥	Potential loss of economic efficiency but requires an analysis of the context condition
⬜	Interaction is irrelevant or not applicable

Table 7 Description of the comparative analysis between network tariffs and flexible connection agreements

Network Tariffs			**Comparative Analysis**	**Flexible Connection Agreements**		
Meta Dim	**Dimension**	**Options**		**Options**	**Dimension**	**Meta Dim**
Temporal	Temporal granularity of charges	Yearly Seasonal (Monthly) Blocks (Daily) Hourly	Group ①: The comparative analysis between these two design dimensions depends on the specific context in which their cross-options are required (blocks in orange). When flexible connection agreements consider payments for curtailments, and network tariff designs already include time-based signals to reduce network problems, customers could be signaling twice, creating scenarios where customers face double charging or double rewarding.	Temporary Permanent	Duration of flexible connection	Temporal
	Temporal granularity of charges	Yearly Seasonal (Monthly) Blocks (Daily) Hourly	Group ②: Misalignments can occur when the time-period of charges and measurements exceeds the predefined duration of curtailments, blocking both mechanisms from being applied simultaneously (blocks in red). Additionally, a consistent definition of charges is achieved if the “Temporal granularity of charges” is at least the same as the “Temporal granularity of the measurements”.	Peak/off-peak Seasonality (Days or periods)	Pre-definition of curtailment	Product
	Temporal granularity of measurements	Yearly Monthly Blocks (Daily) Hourly Quarter hourly				

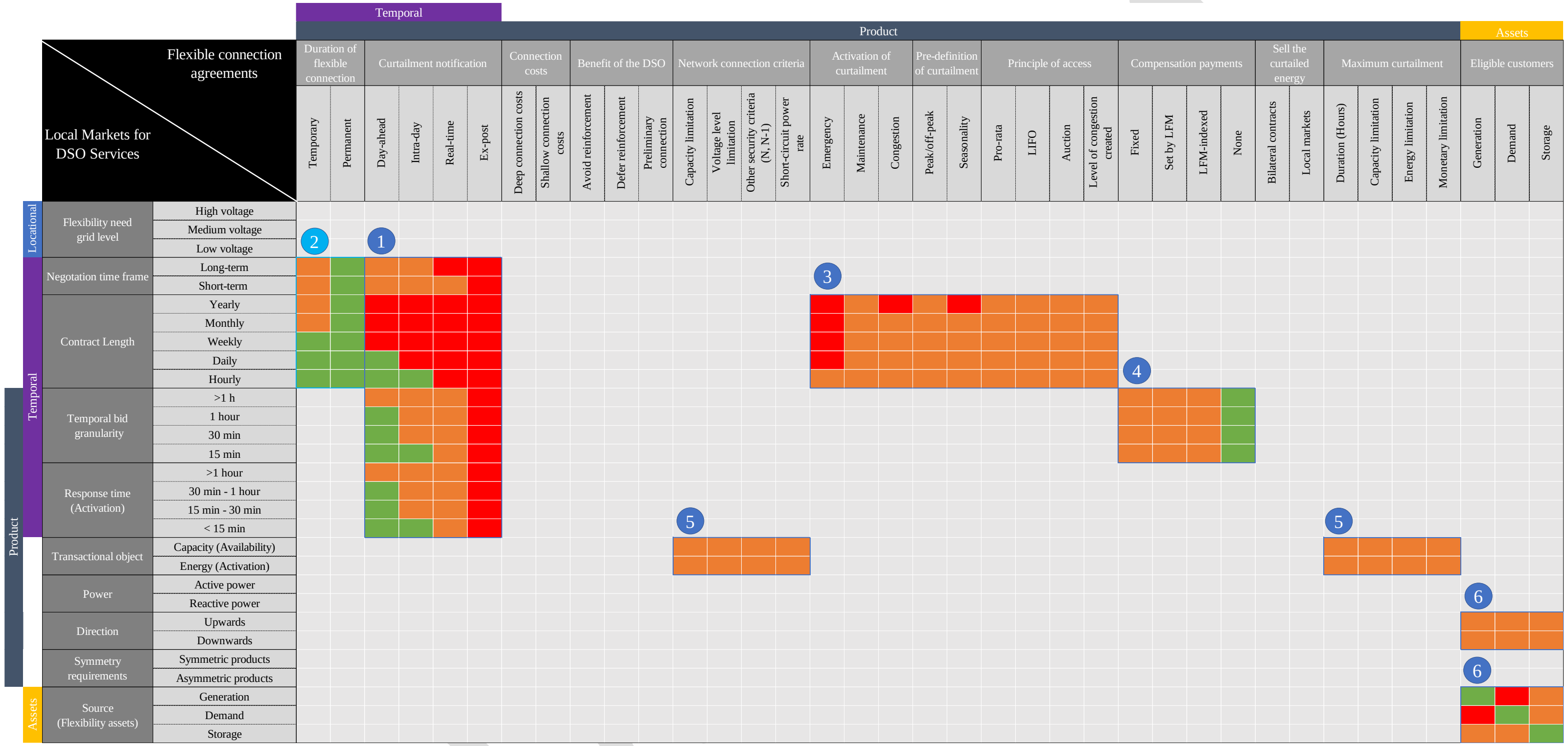
Charges	Cost allocation methods	Average costs Long-term incremental + Residual costs	Group ③: When customers cover the connection costs, it does not cause problems with the cost allocation method (blocks in green). Conversely, if new customers partially or fully assume the connection costs under shallow connection conditions, specific considerations become necessary to avoid double charging through the network tariffs (blocks in orange), when network costs are socialized.	Deep connection costs Shallow connection costs	Connection costs	
				Avoid reinforcement Defer reinforcement Preliminary connection	Benefits of the DSO	
	Charging variable	Fixed Used capacity (Measured) Capacity (Contracted) Capacity (Physical) Energy	Group ④: When charges in network tariffs lack locational or temporal granularity, they may not accurately reflect the network costs and usage patterns of different customer types, locations, or time periods. In these circumstances, flexible connection agreements could overcome these gaps. As a result, when the dimension of the “Charging variable” in network tariffs is set as fixed, it does not create important issues about the “Principles of access” and “Maximum curtailment” (blocks in green). Meanwhile, when there are no compensation payments, it allows interplay with the several options in the dimension of “Charging variable” (blocks in green) since no payments are associated with curtailments and no conditions of double rewarding may arise. The interaction between the design dimensions of “Maximum curtailment” and “Charging variable”, does not lead to misalignments or issues of double charging or rewarding (blocks in green). Exceptions arise in instances where both design dimensions share similar characteristics, for capacity or energy, that require more detailed examinations, in which overlaps in cross-options could lead to efficient misalignment in this interaction (blocks in orange).	Fixed Set by LFM LFM-indexed None	Compensation payments	
				Duration (Hours) Capacity limitation Energy limitation Monetary limitation	Maximum curtailment	

Locational	Locational granularity	System-wide Zonal Nodal	Group ⑤: Low spatial granularity in network tariffs, such as those applied system-wide, facilitates the acquisition of DSO services through bilateral contracts or by participating in local markets for DSO services for the dimension of “Sell the curtailed energy”. It could mitigate potential losses that some customers might face due to compliance with the requirements outlined in their connection contracts. However, a higher spatial granularity for network tariffs, such as nodal pricing, more accurately reflects energy costs through the network. Under such circumstances, a comprehensive analysis becomes necessary. Similar scenarios can be observed with the option of “Compensation payments”, especially when payments are linked to curtailments (blocks in orange). In scenarios where connection agreements do not incorporate compensation payments, interaction with network tariffs typically do not present important challenges.	Fixed Set by LFM LFM-indexed None	Compensation payments
				Bilateral Contracts Local Markets	Sell the curtailed energy
Assets	Customer differentiation	Technology agnostic According to technologies	Group ⑥: Potential issues may arise considering the dimension of “Principle of access” especially when standalone generators are involved, because they are not subject to network tariffs (blocks in orange). Moreover, when network tariffs provide economic incentives for specific technologies, a more detailed examination is also required according to the type of customer. For instance, if some technologies are favored with incentives in network tariffs, as is still the case in some jurisdictions, it can create an uneven playing field. It is especially important for storage technologies, where such benefits can give these customers an advantage over others. While the options of emergency or maintenance in the dimension of “activation” generally do not cause important interplay issues (blocks in green), congestion-related curtailment activation could lead to double charging or double rewarding conditions when compensation payments are associated and require a more specific analysis (blocks in orange). The dimension of “Activation of curtailment” also interacts with the dimension of “Symmetry of the charges”, but it requires analysis in contexts where the “Symmetry of charges” is the same for both offtake and injection and the activation is due to congestions, which requires considerations for battery operations (blocks in orange). This scenario may create an uneven playing field among customers, especially for those who own generation facilities.	Capacity limitation Voltage level limitation Other security criteria (N, N-1) Short-circuit power rate	Network connection criteria
	Symmetry of charges	Same offtake and injection Different offtake and injection		Emergency Maintenance Congestion	Activation of curtailment

	Customer differentiation	Technology agnostic According to technologies	Group ⑦: Although network tariffs should be technologically agnostic, some jurisdictions still opt to provide some incentives for specific technologies. Under such circumstances, challenges may arise when network tariffs incentivize certain technologies, while also flexible connection agreements consider compensatory payments for curtailments, which lead to the risk of double rewarding, or even double charging in case of penalties (blocks in orange). Additionally, depending on the "eligible customer" and this preferential treatment for particular technologies an uneven playing field may emerge by favoring some consumers over others (blocks in orange). Concerning the "Symmetry of charges", while for storage assets, no apparent issues arise (blocks in green), because these technologies could have better control over their injections or withdraws. "Eligible customers" categorized as generation or demand, may experience conditions of unlevel playing field, or also potential double-charging or double rewarding may arise when compensatory payments are involved (blocks in orange).	Generation Demand Storage	Eligible customers	Assets
	Symmetry of charges	Same offtake and injection Different offtake and injection				

Comparative analysis between flexible connection agreements vs. local market for DSO services

Table 8 Pairwise comparison in terms of design dimensions between flexible connection agreements and local markets for DSO services



			Flexible connection agreements	Temporal																																				
				Product																																		Assets		
				Duration of flexible connection		Curtailment notification				Connection costs		Benefit of the DSO			Network connection criteria				Activation of curtailment			Pre-definition of curtailment		Principle of access				Compensation payments				Sell the curtailed energy		Maximum curtailment				Eligible customers		
		Local Markets for DSO Services		Temporary	Permanent	Day-ahead	Intra-day	Real-time	Ex-post	Deep connection costs	Shallow connection costs	Avoid reinforcement	Defer reinforcement	Preliminary connection	Capacity limitation	Voltage level limitation	Other security criteria (N, N-1)	Short-circuit power rate	Emergency	Maintenance	Congestion	Peak/off-peak	Seasonality	Pro-rata	LIFO	Auction	Level of congestion created	Fixed	Set by LFM	LFM-indexed	None	Bilateral contracts	Local markets	Duration (Hours)	Capacity limitation	Energy limitation	Monetary limitation	Generation	Demand	Storage
Locational		Flexibility need grid level	High voltage																																					
			Medium voltage																																					
			Low voltage	②		①																																		
Temporal		Negotiation time frame	Long-term	🟧	🟩	🟧	🟧	🟥	🟥																															
			Short-term	🟧	🟩	🟧	🟧	🟧	🟥										③																					
		Contract Length	Yearly	🟧	🟩	🟥	🟥	🟥	🟥										🟥	🟧	🟥	🟧	🟥	🟧	🟧	🟧	🟧													
			Monthly	🟧	🟩	🟥	🟥	🟥	🟥										🟥	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧													
			Weekly	🟩	🟩	🟥	🟥	🟥	🟥										🟥	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧													
			Daily	🟩	🟩	🟩	🟥	🟥	🟥										🟥	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧													
			Hourly	🟩	🟩	🟩	🟩	🟥	🟥										🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	④												
	Product	Temporal bid granularity	>1 h			🟧	🟧	🟧	🟥																			🟧	🟧	🟧	🟩									
			1 hour			🟩	🟧	🟧	🟥																			🟧	🟧	🟧	🟩									
			30 min			🟩	🟧	🟧	🟥																			🟧	🟧	🟧	🟩									
			15 min			🟩	🟩	🟧	🟥																			🟧	🟧	🟧	🟩									
		Response time (Activation)	>1 hour			🟧	🟧	🟧	🟥																															
			30 min - 1 hour			🟩	🟧	🟧	🟥																															
			15 min - 30 min			🟩	🟧	🟧	🟥																															
			< 15 min			🟩	🟩	🟧	🟥						⑤																			⑤						
		Transactional object	Capacity (Availability)												🟧	🟧	🟧	🟧																🟧	🟧	🟧	🟧			
			Energy (Activation)												🟧	🟧	🟧	🟧																🟧	🟧	🟧	🟧			
		Power	Active power																																					
			Reactive power																																			⑥		
		Direction	Upwards																																			🟧	🟧	🟧
			Downwards																																			🟧	🟧	🟧
		Symmetry requirements	Symmetric products																																					
			Asymmetric products																																			⑥		
Assets		Source (Flexibility assets)	Generation																																			🟩	🟥	🟧
			Demand																																			🟥	🟩	🟧
			Storage																																			🟧	🟧	🟩

Colour-code	Description
🟩	There is no loss of economic efficiency resulting from their interaction
🟧	Misalignments or inefficiencies that reduce economic efficiency due to their interaction
🟥	Potential loss of economic efficiency but requires an analysis of the context condition
⬜	Interaction is irrelevant or not applicable

Table 9 Description of the comparative analysis between flexible connection agreements and Local Market for DSO services

Flexible Connection Agreements			**Comparative Analysis**	**Local Market for DSO services**		
Meta dim	**Dimension**	**Options**		**Options**	**Dimension**	**Meta dim**
Product Temporal	Curtailment notification	Day-ahead Intra-day Real-time Ex-post	Group ①: The degree of interaction is closely linked to the temporal resolution of both mechanisms. The "Curtailment notification" facilitates customers to make informed decisions regarding their participation in LMs for DSO services. Therefore, if the curtailment notification period is adequately known concerning the granularities of the design dimensions of LM for DSO services, there are no interaction conflicts among these design dimensions (blocks in green). On the other hand, discrepancies between these timeframes can lead to challenges that need to be examined according to the specific conditions (blocks in orange). For instance, if "Curtailment notification" is intra-day and "Temporal bid granularity" is greater than one hour, with no payments for curtailments, and "Duration of the curtailment" falls within the duration of market participation, both mechanisms can interact. Otherwise, with payments in a flexible connection, while simultaneously participating in local markets, there is a risk of double rewarding or double charging, which could create distortion in their combined efficiency. Meanwhile, ex-post curtailment notification avoid participation in local markets as curtailment information is unknown to be considered (blocks in red). Being ex-post, the signals are already included in the flexible connection agreement design process, and customers are signaled twice alongside the local market. Additionally, from the interaction perspective, the uncertainty caused by a lack of timely information can pose other challenges. If customers receive a curtailment order after the market has already activated specific bids, customers may be unable to adjust their market strategy in response to the new service requirements. This misalignment could result in a loss of economic efficiency and potential losses for customers.	Long-term Short-term	Negotiation time frame	Temporal
				Yearly Monthly Weekly Daily Hourly	Contract Length	
				>1 h 1 hour 30 min 15 min	Temporal bid granularity	Product
				>1 hour 30 min - 1 hour 15 min - 30 min < 15 min	Response time (Activation)	

Duration of flexible connection	Temporary Permanent	Group ②: If the flexible connection agreements are established as permanent, customers are aware of their timelines and can manage them according to LM for DSO services windows (blocks in green). In the case of a temporary flexible connection, lower temporal granularities can lead to misalignment in the timeframes of both mechanisms, leading to potential conflict that is to be analyzed according to the specific conditions (blocks in orange). For example, if the "Duration of the flexible connection" is one year, and the "Contact length" is longer, the interaction becomes unfeasible as the connection transitions to a permanent status post-one year. On the other hand, in the absence of overlapping durations, the two mechanisms can effectively complement one another.	Long-term Short-term	Negotiation time frame
			Yearly Monthly Weekly Daily Hourly	Contract Length
Activation	Emergency Maintenance Congestion	Group ③: Most cross-options, when considering the interaction between these design dimensions, are highly dependent on the specific context (blocks in orange). For instance, if the "Principle of access" is defined pro-rata, customers have a better understanding of their availability for participation in LM for DSO services. Conversely, under a LIFO approach, the capability of customers to participate depends on their position in the queue for receiving curtailment orders. Additionally, as the temporal resolution of "Contract length" increases, for instance, from hours to years, and considering the various "Principle of access", it is more likely that misalignment issues may emerge between the two design dimensions. Moreover, if the "Activation of the curtailment" is required on an emergency basis, and "Contract length" considering from daily to yearly, misalignments appear, making the combination infeasible because of the lack of time for well-informed market decision-making (blocks in red). Similar challenges may occur when the activation is required by congestion or if the "Pre-definition of curtailment" is seasonal and the "Contract length" is yearly.	Yearly Monthly Weekly Daily Hourly	Contract Length
Pre-definition of curtailment	Peak/off-peak Seasonality (Days or periods)			
Principle of access	Pro-rata LIFO Auction Congestion Created			

	Compensation payments	Fixed Set by LFM LFM-indexed None	Group ④: When flexible connections exclude compensation payments, the two design dimensions can interact without apparent problems (blocks in green) because there is no risk of double signaling to customers. However, the other cross-options must be examined considering the specific conditions. For example, when curtailment considers payments and the temporal granularity of the bids, challenges may occur when both cross-options overlap (blocks in orange), due to customers being double rewarded, leading to distortions in how both mechanisms interact.	>1 h 1 hour 30 min 15 min	Temporal bid granularity	
	Network connection criteria	Capacity limitation Voltage level limitation Other security criteria (N, N-1) Short-circuit power rate	Group ⑤: The design dimensions of “Network connection criteria” and “Maximum curtailment” define the conditions for the flexible condition requirements. Therefore, when interacting with LM for DSO services, it depends on the service required, availability, activation or both, but it is case-specific (blocks in orange). Without compensation payments, if the network connection criteria dimension is based on capacity limitation, and there is a customer with a contract that limits its maximum export capacity to the network due to grid constraints, the customer could offer the available capacity not being used for export as a flexible service to manage network congestion. Conversely, if there are associated payments, this customer could be double signaled, creating double rewarding or double charging conditions.	Capacity (Availability) Energy (Activation)	Transactional object	Product
	Maximum curtailment	Duration (Hours) Capacity limitation Energy limitation Monetary limitation				

Assets	Eligible customers	Generation Demand Storage	Group ⑥: The analysis of the “Source (flexibility assets)” in LM for DSO services, alongside the “Eligible customers” in the flexible connection agreements, entails understanding how different types of assets can be strategically employed and their potential effects on the network requirements. If the customer in a flexible connection is a generation unit and the LM for DSO services also considers generation units, then both design dimensions interact. The same principle applies if the situation involves demand (blocks in green). However, if they are opposed, for example when generation is required but there is demand assets, misalignments can occur due to the type of technology required (blocks in red). In the case of storage, the analysis depends on specific conditions and whether its operations, acting either as generation or demand, are necessary within both mechanisms (blocks in orange). Additionally, the dimension of “Eligible customers” in flexible connection can interact with the dimension “Direction” in LM for DSO services (blocks in orange), given that diverse technologies can offer DSO services in both directions, depending on the network needs.	Upwards Downwards	Direction	
				Generation Demand Storage	Source (Flexibility assets)	Assets

Conclusions

This paper provides critical insights for acquiring DSO services, leveraging the flexibility that third-party resources can provide to the electrical grids using acquisition mechanisms, such as network tariffs, flexible connection agreements, and local markets for DSO services. This manuscript highlights the need to rethink the design practices for these mechanisms since, despite their coexistence in practice, they have traditionally been designed to operate as independent entities. Therefore, novel design practices are required to exploit their combined efficiency due to the synergies that can significantly affect the acquisition of DSO services. Employing qualitative comparative analyses, this paper proposes a structured discussion on the interaction between the acquisition mechanisms to seek potential linkages or significant inefficiencies and to identify the strengths and limitations of their combined design.

The outcomes of the comparative analysis underscore that when mechanism design sends the same economic signals to customers to reduce network usage, customers may face scenarios of double charging or double rewarding, leading to distortions in economically efficient behaviors. These insights emphasize the need for accurate acquisition mechanism design processes to prevent redundant incentives that may interfere with targeted behaviors. Future research should consider quantitative analyses for the different areas highlighted where the results are unclear and case-dependent.

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Declarations

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