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Characterizing flexibility in power markets and systems

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ABSTRACT

The increasing share of variable renewable energy sources creates a need for flexibility resources in the power system operations. This paper presents suggestions for characterizing flexibility, including dimensions of time, spatiality, resource type, and risk in power systems. We present interrelations between these flexibility dimensions, products, services, and suitable market designs. In light of this, we discuss TSO–DSO coordination and optimal flexibility resource allocation.

1. Introduction

The increasing share of variable renewable energy sources (VRES) introduces short-term uncertainty and variability in power systems. Flexibility is needed to maintain a continuous supply–demand balance (Papaefthymiou et al., 2014). There is not a unified definition of flexibility in the literature, but in this study, we take as a starting point: "*Flexibility is the modification in the generation and/or consumption pattern of electricity according to an external signal in order to meet energy system needs.*" (Mandatova and Mikhailova, 2014).

The primary aim of this paper is to characterize flexibility along four dimensions as time, spatiality, resource, and risk profile. The analysis provides insights into flexibility usage in different market designs and systems for decision-makers and utilities. Power markets should provide incentives for optimal valorization and exploitation of flexibility in both short-term allocation (operations) and long-term allocation (investments) to exploit the value of flexibility. In addition, TSO–DSO coordination addresses the allocation of flexibility resources available both at TSO and DSO grid levels. We discuss this in relation to the flexibility dimensions mentioned above.

An efficient market design is essential. In this paper, the efficiency of the existing power market designs, especially short-term and local flexibility markets, are analyzed along the proposed four dimensions to provide incentives for exploiting the value of flexibility from end-users and generators.

We introduce the risk dimension for flexibility characterization. We explain the alignment between flexibility provision, the uncertainties and risks facing flexibility providers, system operators, and generators.

The main contributions of the paper are summarized as follows:

1. Characterize flexibility in power and energy systems in terms of the spatiality, time, resource, and risk dimensions.
2. Discuss the efficiency and suitability of existing and possible new power/energy markets for the exploitation of flexibility and adaptation to the proposed flexibility dimensions.
3. Introduce the risk dimension to flexibility characterization, related products, and market designs.

The paper is structured as follows. Section 2 discusses the dimensions of flexibility as time, spatiality, and technology. Section 3 describes the risk dimension of flexibility and related market designs. Section 4 explains the flexibility products. Section 5 discusses new market designs for flexibility trading and DSO–TSO coordination. Section 6 presents the conclusions.

2. The dimensions of flexibility

Inspired by the *Nordic market balancing concept* (Statnett and Kraftnatt, 2017), this research suggests four dimensions for flexibility characterization: resource, spatiality, time, and risk. This section aims to explain key features of flexibility provision and use. We base the discussion of dimensions on previous contributions to the literature.

2.1. Flexibility dimensions

The authors in Mohandes et al. (2019) investigate flexibility characterization in systems with high penetration of VRES. They propose to characterize the flexibility based on the resource dimension only. Eid et al. (2016) describe four dimensions, including the amount of power,

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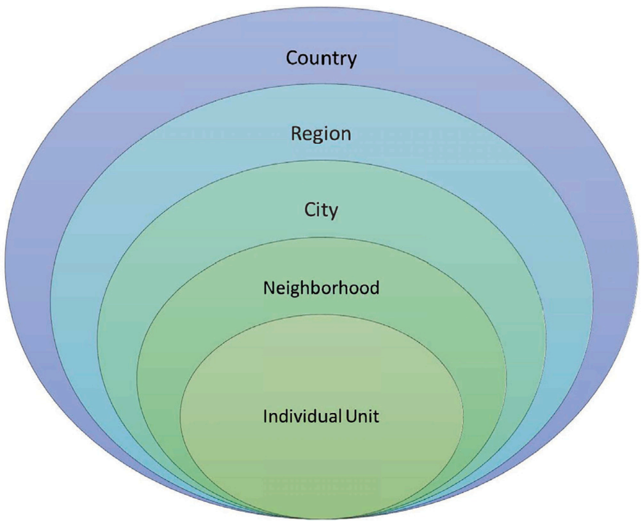

Fig. 1. Spatiality dimension.

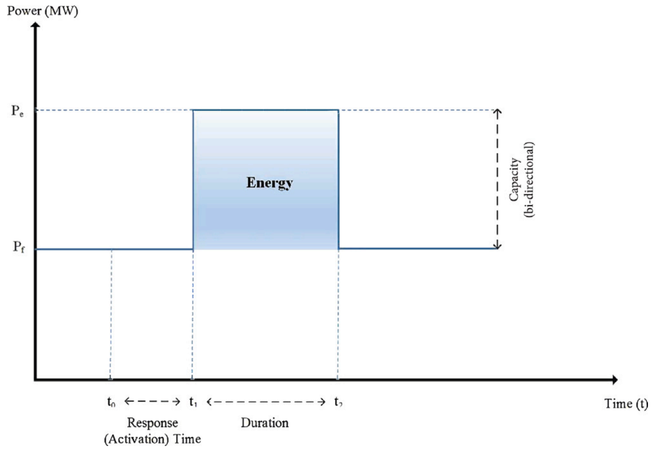

Fig. 2. Characteristics of flexibility in system-wide scale (Eid et al., 2016).

the moment of provision, the duration of the provision, and the location of the resource. Although the study is informative, only DERs are considered as flexibility resources. The authors do not discuss the response time, flexibility resources other than DERs, and risk in flexibility provision. Ela et al. (2016) propose flexibility characterization along three dimensions: absolute power output capacity range (MW), speed of power output change (MW/min), and the duration of flexibility provision. However, they do not discuss the spatiality dimension. Cruz et al. (2018) discuss the primary flexibility resources by considering demand side, supply side, grid side, and storage side flexibility resources; however, markets and flexibility products are not discussed.

In the following subsections, we discuss the concept of flexibility (e.g., MIT, 2016), by characterizing it in terms of four main dimensions: spatiality, time, resource, and risk profile.

2.2. The spatiality dimension of flexibility

In this subsection, we aim to characterize flexibility along the spatiality dimension, i.e., according to the location of the resource. In electricity transmission and distribution grids, the location of the resource connected to the electricity grid is relevant. In some cases, the flexibility need is location-based, as in the case of voltage drops or congestion. The type of flexibility can also make it necessary to consider the spatial dimension. For example, transmitting reactive power over long distances is inefficient due to high grid losses.

The location of a flexibility resource can affect trading and the effectiveness of services provided by transmission system operators (TSOs) and distribution system operators (DSOs) (Kouzelis et al., 2015; of Energy, 2015). The flexibility is limited to specific geographical conditions (spatiality dimension), and it could be traded across geographies, e.g., between houses, neighborhoods, cities, regions and countries (cross boundaries), as illustrated in Fig. 1. For a location needing TSO–DSO interaction, some resources might be used partially by the DSO in the distribution grid and the TSO for the transmission grid (Khajeh et al., 2020). The DSO could use the flexibility to mitigate voltage deviations and congestion, whereas the TSO could use it to mitigate congestion management in addition to supply–demand balance.

2.3. The time dimension of flexibility

To exploit the value of flexibility and use it efficiently, we need to understand the time dimension, i.e., when and how long the flexibility is available to prevent a shortage of flexibility and provide timely valuation. Based on technological characteristics (Ribó-Pérez et al., 2021), market analysis (Valarezo et al., 2021), and system design (Dvorkin et al., 2014), the time dimension can be divided into four subdimensions: activation time, ramping rate, duration time, and market time unit resolution. The activation time concerns how quickly the flexibility resource becomes available for usage. The activated flexibility could be useful in a specific time interval (i.e., the duration) (Biegel et al., 2014; Zhang et al., 2019). The ramping rate of the flexibility resource refers to how fast a flexibility resource can ramp up or ramp down (Knezović et al., 2015). Especially in the case of market designs with short time horizons or ad-hoc system needs, the ramping rate of a resource should be fast due to the immediate need for power (Sanandaji et al., 2015). Based on Eid et al. (2016) three subdimensions (activation time, ramping rate, duration time) are illustrated with some modifications in Fig. 2.

In Fig. 2, the difference between $P_e - P_f$ is the capacity—how much power can be increased or decreased. The symbol t represents time, and t_0, t_1, and t_2 respectively symbolize the flexibility's signaling, starting, and stopping time. The difference between $t_1 - t_0$ is the response (activation) time of the flexibility, while $t_2 - t_1$ is the duration of the flexibility.

The fourth subdimension of time concerns the relevant market horizon. Different market designs are based upon various time intervals and customer needs (Hillberg et al., 2019). Hence, the flexibility provision process should be considered with similar time-related decision-making. Different time properties of resources make it possible to participate in multiple markets, e.g., ancillary services, to restore power quality in a grid. It is possible to observe different flexibility resources relevant from milliseconds to years. The structure of the time dimension with respect to flexibility trading horizons and markets is shown in Fig. 3.

According to the results of the industry survey (managers and modelers) conducted by Helms et al. (2016), with an accurate timing strategy, timing-based flexibility business models in the energy sector could increase their profits while reducing their downside risk. The timing of the market participant could differ for supply-side flexibility resources compared with demand-side flexibility resources. A system operator or a market participant could use only a single flexibility resource with a single timing strategy or harvest multiple resources and have a time-coupled flexibility portfolio.

Overall, the time dimension of flexibility strongly affects resource utilization, resulting in different cost efficiency levels in different market designs. Therefore, we revisit the importance of time in our market design discussions in Section 4.1, in detail.

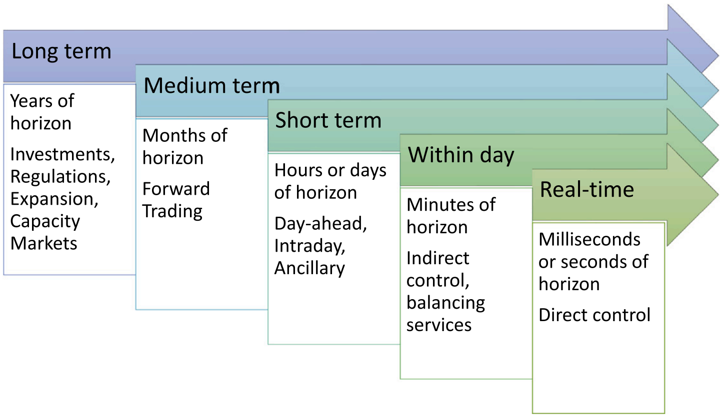

Fig. 3. Flexibility trading horizons and markets.

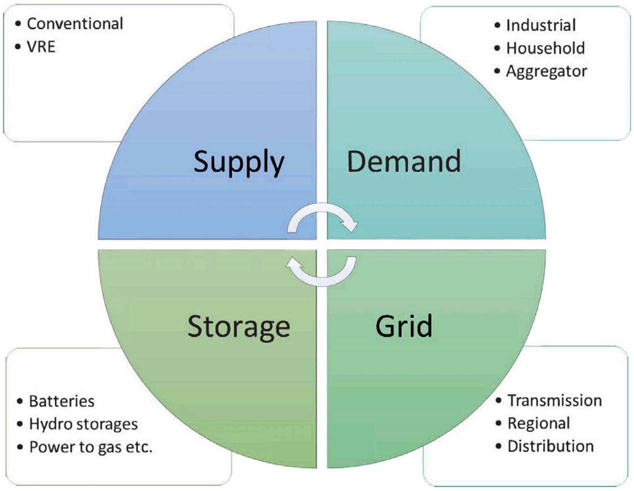

Fig. 4. Resource dimension.

2.4. The resource dimension of flexibility

This subsection characterizes the flexibility along the resource dimension, i.e., the resource technology, stakeholder's profile, and attributes. The resource type of a flexibility asset might vary with different time horizons and locations. In this context, we consider four flexibility resources: supply side, demand side, grid side, and storage side. The four resources are represented in Fig. 4. We characterize the resource dimension of flexibility into supply-side, demand-side, storage-side, and grid-side flexibility subdimensions.

2.4.1. Supply-side flexibility

The uncertain and variable nature of VRES requires higher flexibility in power systems (Papaefthymiou et al., 2014). In this respect, ramp-up and ramp-down rates, time of availability, and start-up and shut-down response times are the primary elements to identify supply-side flexibility (Papaefthymiou et al., 2014; Agency, 2011). Supply-side flexibility resources, such as hydropower plants and gas-fired power plants, are suitable for maintaining the supply–demand balance (Morales et al., 2013).

2.4.2. Demand-side flexibility

Information and communication technologies (ICTs) have made monitoring and controlling consumption profiles in power systems easier. Real-time marginal pricing and time-of-use pricing are vital to provide incentives for leverage flexibility in the supply–demand balance. Coordination between producers and consumers on pricing and supply–demand balance is necessary until storage technologies become cost-efficient.

Demand-side flexibility can be categorized based on its direction of regulation (ramp-up or ramp-down), electrical power composition (differentiation between power and energy), temporal characteristics defined by its starting time, duration (time of availability), and location (spatiality) (Eid et al., 2016; Knezović et al., 2015). Industry, households, and aggregators are flexibility resources on the demand side (Papaefthymiou et al., 2014). Although there is more ongoing collaboration with industrial users for demand-side management, such as load curtailment, also participation by households has been motivated (Mandatova and Mikhailova, 2014; EC, 2016). In households, heating and cooling systems are crucial flexibility sources. Moreover, EVs are emerging as flexibility resources. They can shift their consumption in the short-term (grid-to-vehicle) while selling remaining electricity to the grid (vehicle-to-grid, V2G). Demand-side technologies apply to local problems in short time intervals (e.g., voltage and grid congestion). Thus, demand-side flexibility can improve the overall efficiency of the system (EC, 2016; Badanjak and Pandžić, 2021).

The primary benefit of demand-side flexibility is its response to changes in market supply–demand balance and power quality problems with the support of end-users. In this context, two control strategies are direct and indirect control (Agency, 2011; Haque et al., 2017). Direct control strategies manage demand-side flexibility resources by load shedding or shifting according to system needs and applied by TSO, DSO, or aggregator (Chen et al., 2014; Mortaji et al., 2017; Ottesen and Tomasgard, 2015). The indirect control is applied by the economic incentives to encourage the consumers to change their consumption patterns according to optimal market price signals (Heussen et al., 2012). It is possible to motivate demand-side flexibility resources with optimal price signals such as real-time metering, pricing, and economic incentives. In addition to market efficient and supply–demand balance benefits, demand-side flexibility is beneficial for risk management and reliability, lower-cost electric services, customer services, and environmental considerations (Aghaei and Alizadeh, 2013).

2.4.3. Storage flexibility

Storage flexibility resources act as a buffer to mitigate the short-term fluctuations in electricity production (Morales et al., 2013). Storage units provide power in time by collecting surplus power from VRES or other resources before the provision time (Papaefthymiou et al., 2014). Different storage technologies are pumped hydroelectric, compressed air, flywheels, power-to-gas plants, and batteries (Divya and Østergaard, 2009). According to Divya and Østergaard (2009), Battery energy storage systems (BESS) are the leading storage flexibility resources. BESS can be categorized into centralized and decentralized units for flexibility provision (Flo Bødal et al., 2017). Some researchers regard EVs as battery storage technology due to their capacity for V2G, but in this paper, we consider EVs are demand-side flexibility resources. From a power system perspective, storage flexibility from BESS can provide solutions on short-, and medium-time horizons (Divya and Østergaard, 2009).

2.4.4. *Grid-side flexibility*

Grid infrastructure and reinforcements constitute grid-side flexibility. The definition of grid-side flexibility is the ability of a power grid to engage with demand variations, uncertainty in grid conditions, and changes in the power flow by using grid topology and system operators (Li et al., 2018). Transmission or distribution grid planning and operating may need grid-side flexibility to be efficient (Adams et al., 2010).

Grid-side flexibility is useful due to its physical capacity to cope with changes in the power system. Li et al. (2018) classified grid-side flexibility resources in two items: discrete grid-flexibility and continuous grid-flexibility. Discrete flexibility resources include network topology, transmission expansion planning (TEP), and line switching (LS). Dynamic flexibility resources include reactive power compensation using power electronics, phase angle, optimal power flow, FACTS (flexible alternating current transmission systems), and HVDC (high-voltage direct current).

The limitations of grid-side flexibility are often technical and are challenged by VRES and DERs (Flo Bødal et al., 2017). However, the technical capabilities of grid-side flexibility may lead to reductions in the following respects:

- Thermal ratings: More DER and VRES connections and growing demand can jeopardize the network's installed capacity (thermal ratings).
- Voltage deviation: On-load tap changers (OLTCs) are controlled by automatic voltage control (AVC) schemes in the presence of high, low, and medium voltage situations for voltage preserve.
- Fault level: The short circuit capacity of networks is subject to the thermal and mechanical constraints of the network. Interconnection of DERs and VRES can push the network to exceed short circuit capacity.
- Reverse power flows: Having a reverse power flow makes balancing the low voltage side of the transformer harder and might cause congestion in both transmission and distribution systems.
- Rapid voltage change: Instant increase in power output (ramping-up) might create rapid voltage changes and impact the grid.
- Islanding: If a generator continues to provide power to an isolated grid part, the islanding occurs. Anti-islanding requirements are defined to sustain the distribution of electricity in the grid and prevent islanding.
- Protection: There are three protection challenges for the grid. First, faults in the distribution might cause voltage deviations in the grid. Second, the aggregate generation could exceed the load on the distribution bus, and the flow of power might turn in the reverse direction to the transmission system. Third, a ground source from a generator could change the fault balance between the distribution feeder and the utility system.
- Power quality: Integration of DERs and VRES might decrease power quality and cause voltage fluctuations, flicker, harmonics, and signaling.

With regard to local problems in power grids, grid-side flexibility is related to TSO–DSO interaction. Local network constraint management, voltage optimization, network restoration, and power flow stabilization are major applications of grid operations with flexibility resources (CEN-CENELEC-ETSI, 2015).

3. The risk dimension

The risk dimension of flexibility provision is often neglected in the characterization of flexible assets. Different risk profiles originate from the heterogeneity of technologies and end-users. Also, due to the privacy concerns of participants (e.g., their data have commercial value), there is a lack of information in the market (Zhao et al., 2009). The theoretical relation between risk and uncertainty is outside the scope of this paper, but in this paper, the term risk is used to address the effects of uncertainty and how it affects the flexibility assets to provide flexibility. At one end of the scale, we have firm flexibility provision with a low probability of disruption of the service or failure to provide as promised (e.g., a portfolio of hydropower plants with reservoirs), while at the other end of the scale, we find flexibility products provided by a single windmill with a high probability of disruption or failure to deliver as promised.

To identify the risk, we first have to identify all uncertainty origins in the flexibility provision and their effect on the energy systems and markets. As long as we can measure or quantify the uncertainty of flexibility resources, we can characterize its risk dimension. Since the beginning of flexibility research, most of the literature has highlighted the uncertainty in VRES generation plans. By contrast, risk management studies have emphasized market price or trading risks. There are many sources of uncertainty and related risk profiles in energy systems and power markets. The following are examples of uncertainty types (Kristiansen, 2004; Blaesig and Haubrich, 2005; Buygi et al., 2006; Fang and Hill, 2003; Kirschen, 2003; Linares, 2002):

- VRES generation uncertainty
- Demand uncertainty
- Network availability
- Fuel availability and cost uncertainty
- Wholesale markets price uncertainty
- Policies and regulations uncertainty
- Participation uncertainty (in cases of a market-based approach)
- Duration of the resource uncertainty.

These uncertainties affect the flexibility assets, products, and services from different angles. Furthermore, the risk profiles of flexibility assets in markets impact the market design and process of flexibility usage. During the flexibility procurement and activation process, flexibility is employed to cope with these uncertainties and, at the same time, can potentially be affected by the same uncertainties.

The time dimension is strongly connected to the risk dimension. According to the results of a survey conducted by Helms et al. (2016), a power market participant's short-term planning contains a higher risk of inefficiency than their long-term planning. For example, many market participants conduct their trading agreements months ahead and sometimes one year ahead, and they trade the same resources to multiple markets. If they wait until the day-ahead or intraday markets, their risk could increase due to short-term uncertainties. Similarly, the shortage risk of flexibility products could originate from the contracts and obligations that the flexible asset owner has on different time horizons. In our case, we are concerned with the uncertainty quantification of flexibility resources and the risk of shortage during the provision and activation process. In a California ISO (CAISO) report, the flexible ramping product applies to both 15-min and real-time market designs for upward and downward regulation (CAISO, 2016). These products are designed for situations where there is uncertainty due to demand or renewable forecast errors. The shortage of flexibility ramping products is discussed by CAISO (2016), Navid and Rosenwald (December 2013), Abdul-Rahman et al. (2012), Wang and Hodge (2017). Insufficient flexibility ramping capacity can increase power provision prices and create market imperfections such as supply–demand imbalance.

The risk of failing to deliver flexibility can be foreseen if a robust flexibility metric exists. Lannoye et al. (2012) use a flexibility metric to calculate the time intervals of the flexibility shortage. The authors introduce a metric, insufficient ramping resource expectation (IRRE), that identifies the probability of the system coping with a shortage of flexibility.

Another risk associated with demand-side uncertainty is the *rebound effect* (Berkhout et al., 2000) also known as the payback effect (Esmat et al., 2016). We can observe the rebound effect in the demand profile of a power system when the demand-side participation exits. For example, during peak hours, a demand-side participant could decrease its consumption in the grid and remove the possibility of network congestion. The same participant might increase consumption during off-peak hours due to lower prices to charge an EV or a battery. This behavior increases the demand profile and is subject to congestion in the distribution grid. The main problem is not the amount of demanded power but the time of the demand. The uncertainty of rebound effect occurrence creates a risk to the security of supply in later periods (short-term).

Furthermore, system operators (DSOs, TSOs/ISOs (independent system operators)) are subject to the risk. As shown in Tables 1 and 2, the services that they provide are subject to grid congestion, shortage of flexibility, and market price risk, jointly.

An aggregator stands connected with DSOs to aggregate households' assets to reduce its risk in the system or market. Similar to the system operator's risk profile, the risk profile of an aggregator is a combination of all four dimensions under discussion (i.e., time, spatiality, resource, and risk). An aggregator has many flexibility providers with different resources, spatiality, timing, and risk profiles. Therefore, an optimal portfolio of assets is important for an aggregator because the risk profiles of individuals have an impact on overall risk. To ensure its flexibility supply process, an aggregator needs to find an optimal number of assets in its portfolio based upon risk, resource, spatiality, and time dimensions.

In conclusion, the risk dimension is connected with the other three dimensions and is crucial for flexibility usage. Numerous uncertainties (e.g. fuel, duration, demand, and price) lay at the foundation of the risk dimension for flexibility providers.

4. Flexibility products

This section discusses the flexibility products and their design by considering examples from the industry. A flexibility product is a combination of time, spatiality, resource technology, and risk profile of the provider. According to the need of the power market or system, the product's design might differ. For instance, a flexibility product that addresses voltage problems might have a shorter availability than a product designed for supply–demand balance.

Flexibility services and products are reviewed by Villar et al. (2018) from a general perspective as the flexibility offered by a participant (e.g., an aggregator) to a system operator. The products offered to the TSO for system flexibility (ancillary services) usually are provided by a balance responsible party (BRP), such as CHP, hydropower plants (dispatchable), or zonal interconnections (energy products), which are defined as supply-side flexibility. The products offered to DSOs are mainly for local supply–demand balancing, voltage correction, or grid congestion management by the demand-side, storage-side, or grid-side flexibility resources (supply-side flexibility could also offer these products). In this paper, we analyze flexibility products from a similar perspective.

4.1. Flexibility product design

The structure and purpose of flexibility products originate from the need for an efficient system and market design. In existing market designs, the time dimension determines the economic benefit of a flexibility product in relation to the resource dimension. Many existing flexibility product initiatives are system-wide products, and therefore, the spatiality dimension of the products is not considered (CAISO, 2016; Xu and Tretheway, 2012).

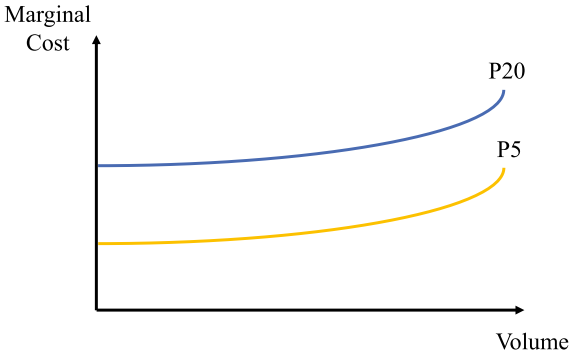

Fig. 5. Cost of flexibility products in the 5-second market (graphs are on the same scale).

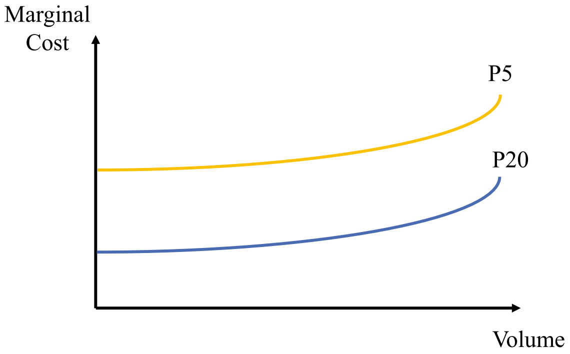

Fig. 6. Cost of flexibility products in the 20-second market (graphs are on the same scale).

Flexibility service providers are heterogeneous along the four dimensions. Products may have different cost profiles for different time dimensions (activation time and duration). This situation leads to a need to consider the optimal alignment of markets where products can be traded. In the time dimension of flexibility (discussed in Section 2.3), the properties of the time dimension, such as ramping rate and duration, are relevant. When designing a flexibility product, essential qualities are how quickly a flexibility asset will respond to the system operator and how long it can provide power.

In an imaginary setting, two flexibility ramping products can be considered: the first has a 5-second activation time and the second a 20-second activation time as their sweet spot in terms of cost, but both can work in a 5-second or a 20-second activation time prior to physical delivery.

The resource with a 5-second activation time will always have lower marginal costs for the 5-second services than the 20-second resources. Similarly, the 20-second resource is better than the 5-second resource for a 20-second flexibility service. If the operator dispatches 20-second technologies in 5-second markets, the operator will lose some efficiency. This economic viewpoint is illustrated in Figs. 5 and 6, where P5 and P20 represent 5-second and 20-second flexibility resources, respectively. Still, it is not practical or economically efficient to prepare a market design for each asset type or resource or for each time dimension. Therefore, the optimal market design needs to address differences in product designs for market and trading efficiency and include different trading and clearing horizons.

Similarly, one could choose optimal spatial resolution when establishing marketplaces to procure power, energy, or capacity. TSO–DSO coordination would be needed, as local and non-local optimal resource allocation would be needed.

Table 1
TSO and ISO services and pricing mechanisms (Birk et al., 2017; Hansen et al., 2013).

TSO/ISO services	ISO pricing	TSO pricing
Electrical energy	Local marginal prices (LMPs)	Zonal
Transmission energy losses		
Transmission congestion		Congestion management markets
Reserves	Co-optimized with LMPs	Balancing markets
Reactive power and voltage control	Regulated prices and bilateral contracts	Regulated prices and bilateral contracts
Black-start		

Table 2
DSO services and pricing mechanisms (Birk et al., 2017; Hansen et al., 2013).

DSO services	Pricing
Electrical energy Distribution energy losses Distribution congestion Reactive power and local voltage control Peak shaving	Regulated or competitive retail supply tariffs
Network connection and reliability Network deferral	Averaged network tariffs

Consequently, the flexibility product designs change according to the need of the system and market participants. Flexibility is evaluated primarily along with the time dimension. However, the spatiality and resource dimensions are equally crucial as the time dimension.

4.2. Product examples

One real-life example of flexibility products is the ramping products in California ISO (CAISO). In CAISO, flexibility products, which are named “flexiramp” by Wang and Hobbs (2016), should be gathered from supply-side resources in the short-term (i.e., less than minutes). Flexibility resources and technologies can provide ramp-up/down products according to regulations and their resource characteristics (Xu and Tretheway, 2012). Consequently, resources for a short and long duration can be distinguished according to their resource technologies, either by the system operator or the aggregator.

In the CAISO market, such products are primarily used for correcting the difference between forecasted demand and realized demand without using major energy providers (Xu and Tretheway, 2012). There is no bidding in wholesale markets for flexiramp products due to the generators’ assumption of zero variable cost. Other markets in the USA have similar products based on ramping rate (e.g., Navid and Rosenwald, December 2013; Parker, 2015), although their market settlement rules are different. Flexiramp products in CAISO aim to achieve two goals: first, improvement in the expected cost (market efficiency) of energy schedules; and second, the provision of incentives for generators to consider the value of ramping in operating and investment decisions. Generators do not provide price bids for Flexiramp (or other ramping products), so prices are based just on the marginal opportunity cost of diverting capacity from energy or ancillary services to meet the ramp requirements. In the CAISO market, the demand curves are calculated every hour independently according to the market design (5-min or 15-min market) and direction (ramping-up or ramping-down). Besides the system-demand curve, each region has different demand curves (Xu and Tretheway, 2012).

Another example of a flexible product is the DS3 plan of Ireland, and its 14 products (flexible DS3) designed to meet system scarcities (Flynn et al., 2016). There are markets for the inertial response (0 to 5 s), reserves (5 s to 20 min), and ramping (20 min to 12 h) products. Ireland’s TSO uses significant short-term (2–10 s) products as operating reserves for frequency correction, reactive power correction, ramping products, primary, secondary and tertiary reserves, and dynamic reactive response.

Along with the spatiality dimension, Irish DS3 and CAISO products have system-wide initiatives in their TSOs and ISOs (CAISO, 2016; Xu and Tretheway, 2012; EIRGRID, SONI, 2017). CAISO’s flexibility ramping products are designed as system-wide products (e.g., CAISO, 2016). However, the ISO might apply some regional constraints according to the power system’s problem (e.g., congestion). In the case of Ireland DS3, flexibility providers are spatially clustered, and they generate a cost-effective strategy for grid operations (e.g., EIRGRID, SONI, 2017). In the case of DSOs (local sense), products show more variety since they include DERs. The reason for using these products is not just for market supply–demand balance but also for mitigation to congestion management, voltage correction, and loss coverage (Villar et al., 2018). Ottesen et al. (2016, 2018), Roos et al. (2014) propose approaches whereby an aggregator participates with multiple flexibility resources in the distribution grid in addition to bidding in the wholesale markets.

Allocation of local and system-wide resources for flexibility is important for the distribution grid and cooperation between the TSO and the DSO (Gerard et al., 2016). According to Villar et al. (2018), flexibility products are provided to local flexibility markets with DERs and other flexibility products to address grid operation issues. Many attempts to establish local flexibility markets in the industry have been reported in the literature (Schittekatte and Meeus, 2020). For example, the NODES marketplace[1] is a universal platform for local flexibility trading (NODES, 2018). In distribution grids, with a pay-as-bid auction design, the NODES marketplace solves congestion problems by using continuous intraday trading. As another example, Zhang et al. (2013) propose an aggregator-based local flexibility market with a flexibility clearing house (FLECH) market to promote DER for active participation in trading flexibility services. In a FLECH market, the DSO or sometimes the TSO acts as a flexibility buyer. In a FLECH design, there are three trading products: bilateral contracts, auctions, and the supermarket. In market design, activation time, duration, and location are relevant to the product types offered. A FLECH design is aligned between the DSO and the aggregator interconnection. Torbaghan et al. (2016) investigated the usage of prosumers’ flexibility in a decentralized perspective and found that the local market structure trades flexibility and solves problems by cost-minimizing objectives. Their research aims to solve distribution grid problems before using the wholesale markets. Furthermore, in France, the TSO proposes capacity contracts as a quantity-based market-wide mechanism to cope with increasing peak demand and incentivize demand-side flexibility for all consumers (de Transport d’Électricité. France, 2014).

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[1] https://nodesmarket.com/about/.

Flexibility products can be designed to combine different flexibility resources for a common purpose, such as fixing voltage deviations or congestion management. Klaassen et al. (2018) combine flexibility from different providers for congestion management in wholesale markets. Their product, flexibility value stacking, is based on multiple flexibility providers combined either in a pool market design or a portfolio by an aggregator for trading in wholesale and balancing markets for congestion management. Flexibility value stacking products are designed as time-based, pooling/portfolio-based, and double serving based. Moreover, Flynn et al. (2016) point out that TSO–DSO interaction is essential for planning and operating the network.

5. Markets for trading flexibility

This section investigates the flexibility pricing in existing wholesale and balancing market designs, and the need for change in these markets. Our discussion includes the possible local markets that address the spatiality dimension. In addition, we evaluate the TSO–DSO coordination on overall flexibility products for system operator services.

5.1. Pricing flexibility in power and energy markets

Flexibility pricing examples from CAISO, MISO (Midcontinent Independent System Operator), and SPP (Southwest Power Pool) markets indicate that the flexibility products are mainly evaluated on DA and ID markets. In these markets, flexibility is characterized by considering the time dimension (i.e., ramping rate) (Navid and Rosenwald, December 2013; Xu and Tretheway, 2012; Wang and Hobbs, 2016; Parker, 2015). Another perspective is the Irish TSO (EirGrid), which proposes products by considering the spatiality, resource, and time dimensions, mainly emphasizing the time dimension due to system needs. Real-time pricing is used for all in flexible DS3 (Flynn et al., 2016; EIRGRID, SONI, 2017). In the French TSO case, capacity obligations and certificates construct the price mechanism, especially for peak-hours electricity provision (de Transport d'Électricité. France, 2014).

A problem with existing market pricing mechanisms for flexibility is the lack of incentives for the flexibility providers (Bouloumpasis et al., 2019), in times of power scarcity and power surplus. In situations when flexibility is provided from demand-side resources, we can observe that market power shifts from the generators to the end-users of electricity (Lund et al., 2015). Su and Kirschen (2009) show that demand-side flexibility resources and bids can outperform conventional price bids and reduce flexibility prices. Therefore, it is essential to incentivize demand-side flexibility in a market design. The ID market design is one of the main means of trading flexibility and incentivizing flexibility resources (Pape, 2018). ID market prices often are close to DA market prices. This convergence has led some researchers to disregard the importance of having different flexibility markets (Garnier and Madlener, 2014). However, in their studies of flexibility pricing, they have not conducted analyzes along the time dimension of flexibility resources and spatial differences.

In some energy-only market designs, providers withhold flexibility for peak load hours (Harvey and Hogan, 2001). Many flexibility providers expect to recover their investment costs by trading their flexibility in peak hours. This strategy is in line with our research findings, such as it is possible to use the flexibility for deferring grid investments and recovering investment costs (Council of European Energy Regulators, 2020).

Höschle et al. (2017) describe the pricing and market mechanism for flexibility trading in the presence of price caps and cost recovery conditions. Price caps in energy markets lead to higher prices; hence, trading flexibility in peak hours increases the power prices (ramp-up in scarcity hours). Price capping might be an option for market mechanisms, but price cap revenues are related to revenues from flexibility trading. Cost recovery for flexibility investments mainly comes from earnings from trading at peak pricing periods instead of off-peak or regular trading periods. Naturally, prices for flexibility are mainly affected by (marginal) costs of technologies and the applied price cap.

From the spatiality dimension perspective, aggregators and system operators can access different resources in transmission and distribution networks. Combining different areas and generators in the same market leads to better allocation of reserves and lower marginal generation costs, especially for supply-side flexibility resources (Nicolosi, 2010; Riesz and Milligan, 2015; Grande and Bakken, 2008; Farahmand and Doorman, 2012). In addition, markets with spatiality attributes, i.e, distribution-level markets, provide solutions to DSO's problems (Badanjak and Pandžić, 2021).

5.2. Local flexibility markets

The introduction of the entity "prosumer" to the power and energy markets changes power market designs (Parag and Sovacool, 2016). The change in market designs from centralized to decentralized and the integration of prosumers into existing markets is investigated by Parag and Sovacool (2016), with respect to four structural attributes: the peer-to-peer model, prosumer-to-islanded microgrids, prosumer-to-interconnected microgrids, and the organized prosumer group model. In the peer-to-peer (P2P) model/markets, prosumers are directly interconnected to buy and sell power and energy from others. In prosumer-to-interconnected microgrids, prosumers provide their services to a microgrid that is a part of a larger grid. The prosumer-to-islanded microgrids comprise prosumers who provide services to independent, non-interconnected microgrids. In the fourth and final market structure, organized prosumers create a trading pool.

A local and consumer-centric market design, such as a local flexibility market (LFM), might be an efficient market design for flexibility pricing and trading. In order to design a local flexibility market, a general list of market design principles needs to be followed before introducing the details of the flexibility trading. According to Newbery et al. (2018), six principles of a good market design are as follows:

1. Correct the market as quickly as possible in cases of failure. By reducing the reliability of subsidiarity, the market imperfection will be corrected as soon as possible.
2. Allow for appropriate cross-country variation in market design. Ensuring the security of supply is a local issue.
3. Use price signals and network tariffs to represent the value of electricity provision services. Include the provision of flexibility. This principle has long and short-term effects such as deferring the investments and sustaining the efficient dispatch.
4. Collect network fixed costs from the market. The difference between efficient prices and regulated prices allows for revenue from end-users.
5. Provide incentives for low carbon investment. Provide efficient risk-averse financing for low-carbon and capital-intensive investments in electricity markets.
6. Retain the flexibility to respond to changing information in the market, such as information relating to lower costs and different technologies.

In addition to the six fundamental market design principles, Ramos et al. (2016) propose four local (flexibility) market design dimensions: temporal, spatial, contractual, and price-clearing.

A local flexibility market requires incentives for valuing flexibility. For more substantial incentives to exploit flexibility from end-users and increase efficiency in the market and systems, LFMs are crucial for specific grid or market purposes. The need for an LFM is specific to each case. Most researchers consider the need for LFMs as decentralized and separate from wholesale markets. Some (e.g., Heinrich et al., 2020), suggest that an LFM should complement the balancing markets. According to Jin, Wu, and Jia (2020), recent studies have provided good insights into an efficient market design for flexibility trading (Jin et al., 2020). In addition, LFMs can be useful for various services, such as market-oriented services, system-oriented services, and grid-oriented services (Minniti et al., 2018). Another detailed LFM modeling, challenges, and implementation review research for grid and market problems are investigated in Bjarghov et al. (2021) by considering blockchain applications for flexibility trading. In addition to local markets, P2P markets could help to utilize more surplus solar production by prosumers (Zhang et al., 2019). However, in Dynge et al. (2021), the P2P markets do not significantly contribute to grid operations in a local sense.

According to the flexibility service or product, for example, mitigation to voltage or congestion management, the market considers the spatiality and time dimensions of the flexibility resources because the voltage needs to be fixed at specific locations in the grid topology (active and reactive power distribution) (Knezović et al., 2015; Heilmann et al., 2020a). With regard to another flexibility service, namely congestion management, it is important to address congestion along with the time dimension (Bouloumpasis et al., 2019). Moreover, LFM requires a continuous consideration of market time, especially in short term grid operations (ID market) (Prat et al., 2021). In the case of the risk dimension, the LFM is required to cope with the market liquidity risk to provide a sufficient amount of power from flexibility resources (scarcity of flexibility). The TSO–DSO coordination and the co-existence of different LFMs have to be considered for higher efficiency for flexibility usage, as aligned with national wholesale markets (Gerard et al., 2018; Tohidi et al., 2018).

5.3. The need for TSO-DSO services and coordination based on flexibility

A system-wide approach to coordination among multiple market participants and operators is needed for the reliability and efficiency of the power system. DSOs can deal with local problems by flexibility trading, while TSOs manage TSO–DSO interaction (Villar et al., 2018; Birk et al., 2017; ENTSO-E, 2015b; Hansen et al., 2013; Zegers and Brunner, 2014). Research reported in Gerard et al. (2016) and Gerard et al. (2018) suggests five different coordination models: centralized ancillary services market, local ancillary service market, shared balancing responsibility, common DSO–TSO ancillary service market, and integrated flexibility market. In the centralized ancillary services model, a single market with only a TSO as a buyer is designed without the participation of the DSO. In the local ancillary service market model, the DSO is the user of the local flexibility and establishes a local market. The shared balancing responsibility model indicates that the local markets have to provide lower entry barriers to DERs for TSO–DSO coordination. In a common TSO–DSO ancillary services market model, the TSO and the DSO collaborate to use flexibility resources optimally. Lastly, the integrated flexibility model increases the possibilities for BRPs to solve supply–demand imbalances as well as market liquidity. Another perspective for TSO–DSO coordination schemes from the literature is presented in Givisiez et al. (2020) for flexibility usage. In addition, Minniti et al. (2018) depicts the co-existence of TSO and DSO for the same flexibility resources in certain situations.

The provision of flexibility services by the TSO and DSO are related to voltage, congestion, balancing, black-start, and interoperability for coordinated protection (Zegers and Brunner, 2014). There are ongoing discussions about pricing these services based on flexibility assets, as we have mentioned in Section 5.1. System services that are provided by the DSO and the TSO (or ISO) are listed in Tables 1 and 2, according to Birk et al. (2017) and Hansen et al. (2013).

5.3.1. Interaction along with flexibility resource

The distinction between DSO and TSO services in Tables 1 and 2 originates from the voltage and frequency requirements of the system. The TSO considers frequency and grid congestion issues, whereas the DSO focuses on voltage deviation, grid congestion, and network loss issues. The requirements of frequency deviations for conventional resources (supply side) is much stricter than requirements for demand-side resources. The voltage should be higher when electricity is injected into the grid from the supply side but should be lowered when it reaches end-users for utilization (high-voltage to the low-voltage grid). Therefore, local resources managed by the DSO have different voltage requirements than the non-local resources owned by the TSO. As a result, besides voltage and frequency challenges, the congestion management for an entire grid is diversified by the DSO and TSO concerning their local flexibility and grid resources. TSO and DSO services differ because their products (e.g., flexibility resources) differ.

According to Birk et al. (2017), DSO and TSO services can compete within the same level of the grid. Moreover, flexible power resources can compete in DA, ID or balancing markets as either energy or power, but not as capacity. Flexibility resources should be bid to markets that are most profitable for them. Furthermore, the bidding process should provide optimal incentives and price signals for market participants to continue (Birk et al., 2017). In this regard, the reduction of market barriers would be helpful, as stated by MacDonald et al. (2012).

5.3.2. Interaction along spatiality

System operators should communicate and coordinate flexibility resources according to their spatial responsibilities. The spatial differences among flexibility assets impact their technology and their mitigation of grid problems (Birk et al., 2017). As illustrated in Fig. 1 resources located in different geographies have different incentives, technologies, contracts, and market power. In particular, we cannot expect flexibility resources from a transmission level (high-voltage) to act similarly to a small demand-side resource in a distribution grid.

Both system operators (i.e., TSOs and DSOs) provide congestion management services that are increasingly important due to expanding local power generation. DSOs can use demand-side and storage-side flexibility resources for local congestion management, whereas TSOs can use supply-side and grid-side flexibility for transmission grid services. These facts stress the coordination of flexibility resources. The geographical information tags for DSO and TSO market bids are presented by ENTSO-E (2015b) coordinating flexible resources.

5.3.3. Interaction along time

Flexibility assets can provide long-term and short-term solutions for markets and services. Furthermore, a short-term resource can bid for a long-term perspective, and at any point in time, there might be conflict (or overlap) among the contracts. A DSO could use its resources for local voltage balancing, while a TSO might want the same resources for congestion management in the grid. Such situations need a high level of coordination between the TSO and DSO. As shown in Tables 1 and 2, the DSO and TSO provide different services, but both provide services for grid congestion management.

The coordination of the DSO and TSO should be evaluated in two time periods, such as short term and long term. Currently, there is ongoing TSO–DSO coordination in long-term planning in the literature and the industry. Smart-grid initiatives, network expansion planning, and research programs are examples of long-term collaboration (Birk et al., 2017; ENTSO-E, 2015a). However, the coordination between the DSO and TSO should include short-term solutions for congestion, voltage, and frequency problems in further consideration of new market designs. Moreover, the TSO–DSO coordination mechanism in the case of LFM needs to be aligned with existing wholesale markets (Minniti et al., 2018).

5.4. Need for change in existing power markets

The integration of VRES and the transition of energy systems affect the management, technology, and economics of market designs and power systems from centralized to decentralized and from a regulated structure to a deregulated structure (Eid et al., 2016). Comparing existing market designs, their shortcomings, and participant profiles is

Table 3
Structure of flexibility trading in current power systems and market designs.

Time interval	Market mechanism	Product	Flexibility provider	Spatiality	Connection to grid	Uncertainty
Real time	Direct control	Power	Household appliances	Local	Distribution	Resource duration, Demand, Congestion
Within day	Indirect control		Household appliances, EVs	Local	Distribution	
	Balancing markets	Energy and power	EVs, Industrial DS, Aggregators	Local and non-local	Transmission, Distribution	Resource duration, Demand, Congestion, Fuel availability and cost, Wholesale market price, VRES generation
	Ancillary services		Aggregators, Conventional, Renewable			
Short term	Intraday	Energy	Aggregators, Conventional, Renewable			
	Day-ahead	Energy	Aggregators, Conventional, Renewable, Storage			
Medium term	Forward markets	Energy and power	Conventional, Renewable, Storage			Demand, Fuel availability and cost, Wholesale market price, VRES generation
	Capacity markets	Capacity	Conventional, Renewable			Demand, Fuel availability and cost, Wholesale market price
Long term	Network expansion and investments	Capacity	Network reconfiguration, Grid expansion, Capacity expansion			Network investments, Policy and regulation

crucial to understanding the need for change in market designs. Using DERs and VRES increases the risk for power markets and systems due to the uncertainty in generation and consumption profiles. A change in power markets needs to consider the risk profiles of intermittent resources to increase efficiency.

The main problems regarding flexibility procurement and employment in existing market designs are time, spatiality, and resource dimensions (risk profile is individual). In the case of resource dimension, the variability of flexibility resources needs to be considered in the markets. Different market barriers and system needs require specific resources during flexibility procurement (Holttinen et al., 2013). In the case of the time dimension, as we discussed briefly in Section 4.1, regarding the time of availability and duration of the flexibility product, market gate closure and operational times should be arranged (Huo et al., 2020). If the flexibility needs to be procured for grid operations in addition to supply–demand balance, e.g. voltage correction, spatiality dimension becomes more important for active and reactive power transmission and distribution. In national markets, spatiality is barely considered (Huo et al., 2020; Heilmann et al., 2020b).

In order to increase the integration of renewables and efficient procurement of flexibility resources, market designs and flexibility products should be evaluated dependently. Market barriers (national) could be reduced (Xu, 2019), the flexibility resources could be evaluated according to their technology and time dimension (Lund et al., 2015), especially for demand-side flexibility, as we stated in Section 5.1. For spatiality, the local (flexibility) market could be introduced to increase market volume and efficiency (Heilmann et al., 2020b; Cramton, 2019; Henriot and Glachant, 2013). In addition, DSO–TSO coordination has vital importance for flexibility usage to diversify or aggregate flexibility resources along our dimensions (Khajeh et al., 2020).

A structural comparison of flexibility provision in the current market situation and a basic understanding of the need for change in power systems and markets is presented in Table 3. Originally, Eid et al. (2016) presented a similar version of this table with only DERs. For this reason, we propose an extension with all flexibility technologies, in a time-coupled context, considering our four dimensions, in addition to flexibility products and related market mechanisms. Our novel expansion is the introduction of uncertainty and risk in Table 3.

The mapping between the flexibility resources, markets, and dimensions in Table 3 provides an overview for this paper. Initially, the table presents the time dimension and its cover on all other elements. Single or multiple market mechanisms trade flexibility on every time scale. This overlapping time structure allows using the same flexibility product and provider on multiple markets and services. The crucial point here is that the resource and provider of the flexibility product change from power only products to capacity products along with the increasing time horizon. For example, in real-time flexibility trading, we observe power-based products from demand-side flexibility whereas, in medium-term markets, supply-side flexibility providers trade with energy and capacity products. Concerning these, the spatiality and number of flexibility providers change. For instance, in shorter time scales, utilities or operators tend to use local products and market mechanisms; however, they procure flexibility from non-local (national) products in longer time horizons.

This variety also introduces the significance of DSO–TSO coordination for considering the flexibility provider's grid connection (distribution or transmission network). The uncertainty and related risk profile dimension is novel. The exposed uncertainty by the flexibility providers is related to the resource's technology and time scale. Besides the long term uncertainties, the demand uncertainty is always present. Price and production uncertainty are obvious in short and medium terms along with other operational risks. In the long term, investment and regulations risks affect the flexibility provision. The discussion about the effect of short term uncertainty on long term decisions can be found in Seljom and Tomasgard (2015).

6. Conclusion and outlook

This paper proposes four dimensions (i.e., time, spatiality, resource, and risk) to characterize flexibility. To exploit the value of flexibility and investigate its optimal usage, we analyzed the suitability of existing energy and power markets for both short term and long term purposes, based on the literature and industry reports. The design of flexibility products and real-world examples are evaluated along our four dimensions. In addition, we emphasized the DSO–TSO coordination for flexibility usage on different grid scales.

There is a strong dependency between the four dimensions and the efficiency of flexibility allocation in existing and new markets. In order to use flexibility from various resources, existing markets should reconsider their barriers, time scales (gate closure and physical delivery), and locational limits. A local flexibility market might be needed for an efficient valuation of the flexibility and allocation of resources. TSO–DSO coordination is essential at different levels in the networks to provide services based on flexibility with optimal resource allocation over time and space.

Declaration of competing interest

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

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