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Market design of regional flexibility markets: A classification metric for flexibility products and its application to German prototypical flexibility markets

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Market design of regional flexibility markets: A classification metric for flexibility products and its application to German prototypical flexibility markets

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Abstract

With a growing number of distributed energy resources, the electricity network is challenged with a higher quantity of technical problems such as capacity congestions and over- or under-voltages. One often-discussed approach to solve these problems, especially in the European zonal electricity system, is regional flexibility markets. We provide a novel metric for the design of flexibility products by combining technical requirements with a background in auction theory. This is a valuable contribution to the discussion of regional flexibility markets, which currently occurs on a largely technical or conceptual level. The metric structures 23 product parameters in four stages of different abstraction levels. By applying this metric to five flexibility market approaches used in current German research projects, we demonstrate its usability for consistent description and comparison of flexibility products. Therefore, the metric we have developed, is a powerful instrument for structured analysis and assessment of the vast diversity of approaches to flexibility markets and products at a high level of detail. This metric can empower national and international policy makers and practitioners in developing and assessing flexibility markets holistically and can help to simplify the implementation of best-practice solutions.

Keywords: smart markets, market design, electricity product design, flexibility market

JEL classification: D47, L94, Q41

1. Introduction

As the current energy transition progresses, there will be a growing number of distributed energy resources in electricity networks. These include renewable power plants (e.g., wind turbines, photovoltaic systems) as well as electric consumers (e.g., electric vehicles, heat pumps). As a result of this transition, the operation of electricity networks, especially distribution networks, faces a number of challenges. One anticipated problem is a growing number of capacity congestions in electrical lines and transformers as well as over- and undervoltages in some nodes of transmission as well as distribution networks. This is particularly relevant with a zonal market design, as is this case in the European Union. The state-of-the-art approach is to solve these problems technically with the expansion of the network by additional power lines, transformers and other assets. Addressing congestions by expanding the network to meet the exact amount of electric power required, is often seen as economically inefficient and time and resource consuming ([European Distribution System Operators for Smart Grids, 2014](#)). Therefore, a number of alternative approaches that aim to coordinate flexible supply and demand have been discussed by researchers as well as practitioners.

In general, flexibility can be defined as a modification of electrical parameters (e.g., generation or consumption of power) in reaction to an external signal to support the power system stability ([Villar et al., 2018](#)). There is a lively discussion regarding whether and how flexibility can and should be used in the future energy system, particularly for network services. The first part of the discussion is of a technical nature and attempts to understand the conditions under which the use of flexibility can solve the underlying technical problems in a permanent and reliable way. The second part of the discussion focuses on organizational and economic aspects of using flexibility. In particular, a wide spectrum of incentive systems for using flexibility is analyzed and discussed. One prominent solution is regional flexibility markets, which are implemented in the context of a zonal market design. Such markets can be used as platforms in which owners of distributed energy resources can offer their flexibility to network operators for solving problems such as congestions and voltage problems. If properly defined, this market-based solution may help to reduce network expansion needs and, hence, may reduce the overall system costs.

The idea of a market-based use of flexibility in distribution networks as well as in the transmission network is in line with the current development of the European legislation, the “green energy package” ([European Commission, 2019](#)). The Electricity Directive, which is part of this legislation package, claims the possibility for network operators to procure flexibility in a transparent and non-discriminatory way, considering all types of technologies.

This paper focuses on the market design of regional flexibility markets for network services. We develop a metric for the classification of different flexibility products by bringing together the technical background of grid supporting use of flexibility with aspects of classical auction theory. To the best of our knowledge, this is the first metric to describe the structure of flexibility products in this level of detail. This metric empower national and international policy makers and practitioners in developing and assessing flexibility markets holistically and therefore help to simplify the implementation of best-practice solutions. Furthermore, this metric help practitioners as well as researchers who develop, discuss and improve approaches to regional flexibility markets, which aims for a solution to current network congestions and a reduction in extensive network expansion.

To test the utility of the developed metric, we used it to compare the current approaches of five pilot projects in Germany. These projects within the SINTEG program ([Federal Ministry for Economic Affairs and Energy, 2019](#)) aim to demonstrate showcases for the future energy system

with high shares of renewables, in particular with respect to market-based approaches to network supporting flexibility use. The metric was used to facilitate a detailed analysis of the structure of a flexibility market approach, which can be used as a basis for the evaluation of the integrity of specific approaches. Using this metric, future work can elucidate the advantages and disadvantages of individual concepts and give specific recommendations for the design of future flexibility products.

The remainder of the article is organized as follows. Section 2 reviews the literature on flexibility markets. Section 3 discusses the general requirements for the design of flexibility markets. Section 4 presents the general design space of auction design and the implications of the requirements discussed in Section 3. Section 5 discusses and structures the design space of flexibility products. Section 6 uses this structure to compare five current approaches in Germany. Section 7 presents our conclusions and the policy implications of this work.

2. Regional Flexibility markets – literature review

There is a wide field of academic research investigating the use of flexibility in the energy system. Villar et al. (2018) presented an analysis of the literature regarding flexibility products and markets. The authors clustered flexibility products and market approaches into flexibilities for the use of transmission system operators (TSOs), which can be provided from actors connected to the transmission system or the subordinate distribution system, and flexibilities for the use of distribution system operators (DSOs), which must be located in the respective distribution system. Villar et al. (2018) name the following use cases for flexibility: TSOs' balancing power, TSOs' and DSOs' congestion management, and TSOs' and DSOs' power quality (voltage) control.

When focusing on the market-based use of flexibility in distribution networks, the academic and semi-academic literature can be divided into conceptual works that focus on organizational aspects, technical-oriented papers, economic-oriented papers and implementation-oriented research projects. Several examples of these works are summarized below.

With regard to works that focus on organizational aspects, Apel et al. (2014) discussed the concept of regional flexibility markets in which DSOs act as demanders for network supporting flexibility that is provided by all sorts of prosumers. The six use cases (master data, day-ahead planning, flexibility offering, flexibility contracting, using flexibility and using ultima ratio) describe the fundamental processes of the market. Ecofys and Fraunhofer IWES (2017) discussed the topic of “smart markets” in the context of the German energy system and defined six general models of smart markets and how they could be integrated into existing structures. Gerard et al. (2016) focused on the coordination mechanisms between DSOs and TSOs and discussed different coordination schemes with the perspective of the European interconnected system. Holmberg and Lazarczyk (2015) and Hirth and Schlecht (2019) analyzed different electricity market designs on the system level with a focus on the handling of network congestions. In both of these papers, the authors discussed the risk of false incentives (referred to as the “Increase-Decrease Game”) was discussed in connection with regional flexibility markets.

More technically oriented articles have focused on the feasibility of flexibility concepts and have often used simulations in exemplary settings. For example, Kornrumpf et al. (2016) conducted a one-year simulation of a medium-voltage network with different flexibility options in a flexibility market framework. The authors showed that such a market can contribute to a secure network operation in distribution networks and thus limit the necessity of network enhancement. Torbaghan et al. (2016) used a model of a local market consisting of a day-ahead element as well as an intra-day element, and formulated the procurement strategy of the DSO as an optimization problem.

Lamparter et al. (2016) developed and discussed an agent-based market model for trading flexibility in the “smart grid”. Schermeyer et al. (2018) compared different congestion management approaches using an optimal power flow program in a one-year simulation. The authors found that a cost-based mechanism can help to use more flexibility options and decrease the overall cost of congestion management.

Overall, the aforementioned literature lacks detailed analyses of the market structure and mechanisms as well as the tradeable products. A more economic approach by Dauer (2016) followed Neumann (2007) and used a structural process for designing an allocation mechanism for local flexibility (referred to as “market engineering”). In this approach, the bidding language and the pricing rules are developed with respect to the underlying mechanism theory and evaluated by market simulations.

A more implementation-orientated study was presented by Ding et al. (2013) in connection with Heussen et al. (2013) and Zhang et al. (2013). These works proposed a clearinghouse concept to coordinate the DSO’s demand for flexibility with the potential supply. In a year-ahead procurement process, the DSO could obtain six different products in the categories of congestion management and voltage control.

There has also been significant research activity in the German and European electricity sector (see, for example, Federal Ministry for Economic Affairs and Energy, 2019). Four of the five SINTEG projects demonstrate at least one regional flexibility market approach. The relevant projects and prototypes are analyzed in Section 6.

Special attention must be devoted to the local aspect of flexibility use. Most of the aforementioned literature highlights the fact that there is a sensitivity between the location of a technical problem to be solved and the location of the flexibility as a potential solution. In some cases, the problem is discussed on a more conceptual level (e.g., Apel et al., 2014); in other cases, it is transferred into a model parameter (e.g., Kornrumpf et al., 2016). Finally, sometimes the problem is treated in an implicit way (e.g., as the necessity for TSO-DSO coordination, see e.g. Gerard et al., 2016).

To summarize, there is considerable research occurring in the field of regional flexibility markets; however, this often occurs on a more conceptual level and is mainly technically oriented. Only a few studies have analyzed an economic-oriented market design with detailed descriptions of product and auction mechanisms, and none have combined economic- with technical-oriented analyses. Prototypical markets are used in some projects. Overall, there is a lack of research regarding structured analyses of the market design space of regional flexibility markets.

3. Technical background of regional flexibility markets

The first step when discussing the design of new flexibility markets is to examine already existing energy or even flexibility markets (e.g., for short-term energy trading or balancing power). When considering European balancing power markets, a heterogeneous landscape of different market models with different product specifications and trading rules can be seen (Ocker et al., 2016). The variety of possible market designs seen in already existing and operational markets shows that different market designs have unique advantages and disadvantages. Consequently, there is a lively discussion regarding these markets and a continuous adaption of the rules. A similar discussion related to the market design of future regional flexibility markets has already begun. As an important part of this discussion, The present paper provides insights into the design space of flexibility products by developing a new metric for flexibility products.

3.1. Technical aspects of the network operators as flexibility demanders

The network operator's aim is to operate his network in the most efficient way and reduce the overall cost of network operation and planning (European Distribution System Operators for Smart Grids, 2014). To achieve this, the network operator will define technical requirements for the traded products and the market mechanism. Three fundamental characteristics that describe flexibility are the amount of flexible power, the reliability and the location of the flexible asset (European Distribution System Operators for Smart Grids, 2014). Information about these properties, especially the location, must be disclosed to the network operator in order to determine the value of a flexibility in relation to a potential problem (Kornrumpf et al., 2016). Furthermore, the processes of a flexibility market must be consistent with the existing operation processes of the network operators, such as monitoring and forecasting the state of the network and identifying technical problems. The latter point does not only concern a single network operator, but also all interconnected system operators. The possibility of TSO-DSO coordination is, therefore, an important requirement for the overall market design (Oleinikova and Obushevs, 2015; Vries and Verzijlbergh, 2015).

3.2. Technical aspects of the flexibility suppliers

On the other side of the market are the potential providers of flexibility. From a purely technical point of view, these can be electrical storages, flexible demand (demand response) or flexible producers of any size (Vries and Verzijlbergh, 2015). However, due to the ongoing energy transition, future flexibility-providing assets will often be relative small units in industrial companies or even households. In contrast to conventional power plants that provide flexibility on the transmission-system level, these assets are not primarily designed for a flexible operation. Consequently, for a flexible operation, additional planning aspects (e.g., user comfort) must be considered (Petersen et al., 2012).

When aggregating these assets in virtual power plants, there can also be difficulties due to the local relationship between demand and supply. In a large virtual power plant, inconsistencies can appear; for example, some units may have no effect on an identified problem, but the virtual power plant offers flexibility including these assets. On the other hand, a growing number of units reduces the risks of default and simplifies the forecasting of potential flexibility in a number of stochastic producers or consumers (Kouzelis et al., 2015). Finally, economic aspects for suppliers must be respected, because every flexible unit or (flexible) virtual power plant must plan its use in the most economical way. The alternatives of different marketing opportunities are not new, as trading on the energy market and providing flexibility on balancing markets can be seen as competing alternatives (see, for example, Müsgens et al., 2014). All of these factors lead to an optimization problem for potential suppliers, including technical and economic aspects as well as questions of portfolio management and the possibility of participating in different markets.

3.3. Aspects of communication technology

A suitable communication technology is a requirement, but also an enabler for most models of flexibility use, not only flexibility markets. With the development of the smart-meter infrastructure, more actors can participate in the energy system and provide their individual flexibility (Katz, 2014). In general, more complex flexibility approaches lead to higher requirements for the enabling communication technology. Such requirements include real-time measurement of electricity consumption or production, a two-way communication path and the ability to submit an activation signal to a flexible device (Woo et al., 2014).

In this context, [Lehmann et al. \(2019\)](#) defined four dimensions of the communication of flexibility. First, the flexibility offer describes the possibility of flexible behavior in a defined model. It must be transported to the flexibility demander via a communication path. Second, the signal of the flexibility request can have different forms, such as an explicit direct value or implicit demand via different prices. Indirect requests via limiting values are also conceivable ([Ecofys and Fraunhofer IWES, 2017](#)). Third, the pathway of the flexibility request must be defined technically. Finally, the responsibility for the activation of the flexibility can vary between the supplier and the demander. A consistent communication standard must respect all of these dimensions in order to avoid misinterpretations of the agreed flexible behavior.

3.4. Summary of technical aspects

The market design of a flexibility market must consider both the supply side and the demand side of the market. In line with this, [Dauer \(2016\)](#) defined a number of fundamental requirements for a flexibility market, which are a compact bidding language and the consideration of different flexibility characteristics in terms of type, range, portfolio and valuation per unit. These requirements are consistent with the aspects discussed above. Furthermore, the market design must be in line with the following claims:

- (i) There must be well-defined rules and communication standards ([European Distribution System Operators for Smart Grids, 2018](#); [Woo et al., 2014](#));
- (ii) Flexibility offers should have a preferably high reliability ([Villar et al., 2018](#); [European Distribution System Operators for Smart Grids, 2018](#));
- (iii) There must be possibilities of coordination between DSOs and other DSOs, DSOs and TSOs, and between DSOs/TSOs and other market participants. ([European Distribution System Operators for Smart Grids, 2018](#); [Villar et al., 2018](#); [Vries and Verzijlbergh, 2015](#)); and
- (iv) There must be an outside option if the market fails ([German Association of Energy and Water Industries, 2015](#)).

All of these requirements address the fundamental problem of market liquidity. The market can only operate effectively and efficiently if the technical, economical and organizational frame for both sides of the market is consistent with these requirements.

Figure 1 summarizes the main challenges and special tasks encountered when designing a regional flexibility market. Both the demand and supply sides of the market have individual technical requirements that must be respected. This is the exogenous base for a flexibility market design. The task of market design itself can be divided into auction design and product design. Auction design describes the rules and mechanisms of how the trading process is structured. Product design addresses the question of which trading objects can be exchanged on the market. Both issues overlap in several ways, which will be discussed in the following sections.

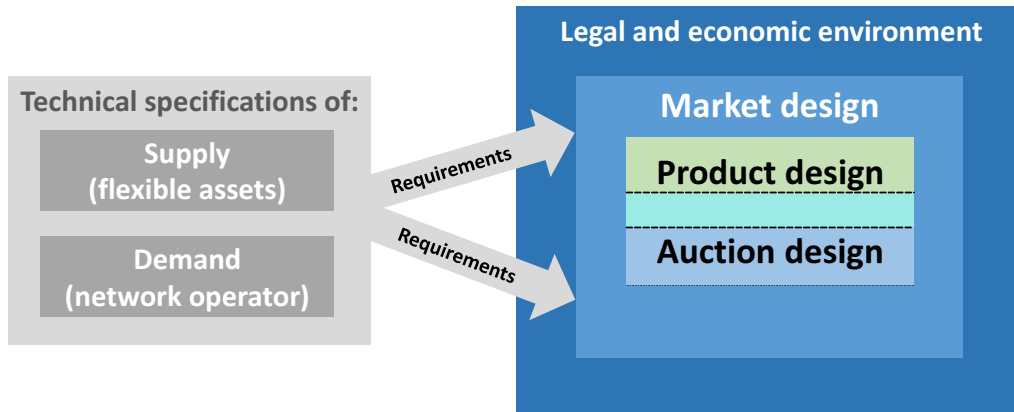


Figure 1: Market design of flexibility markets

4. Aspects of auction design

Auction theory has been a topic of academic research for more than 30 years. In the last two decades, auction theory has gained importance in the context of digital trading in the commercial as well as the private sector. Because of the wide field of research and application of auctions, a structured analysis of the term and the design space of auctions is necessary. Such analyses have been described in several academic works (e.g., [Parsons et al., 2011](#); [Wurman et al., 2001](#); [Buer, 2012](#); [Teich et al., 2004](#); [Abrache et al., 2007](#)), which are the basis for the work at hand.

We followed the auction definition of [McAfee and McMillan \(1987\)](#): “An auction is a market institution with an explicit set of rules determining resource allocation and prices on the basis of bids from the market participants.” Consequently, auctions can be used to trade any sort of products, often (but not necessarily) as a monopoly (selling auction) or as a monopsony (procurement auction) ([McAfee and McMillan, 1987](#)). Thus, auctions can be interpreted as a subset of negotiations with a structured bidding and restricted exchange of information between the parties ([Bichler et al., 2003](#)).

These general definitions of auctions give a broad range of design options, which are widely discussed in the existing literature. Therefore, we used one of the existing frameworks and analyzed selected special aspects in connection with regional flexibility markets. We followed the approach by [Buer \(2012\)](#) based on [Abrache et al. \(2007\)](#) and [Teich et al. \(2004\)](#), which aimed to characterize auctions by describing parameters in the following four groups: organization, goods, bids and winner determination. Note that these four groups have overlaps; thus, some parameters can be allocated in more than one group.

4.1. Organization

The organization of an auction describes the fundamental structure of the trading mechanism. Aspects of transparency and access of different participants are also defined.

Organizational aspects can be of a descriptive nature, such as the ratio between sellers and buyers, the role of the auctioneer or the structure of the bidding process ([Buer, 2012](#)). In addition, organizational rules, such as access criteria ([Buer, 2012](#)), the existence and structure of trading fees and the information revelation rules ([Wurman et al., 2001](#)), especially for the visibility of bids ([Buer, 2012](#); [Parsons et al., 2011](#)), must be described.

In the context of regional flexibility markets, some of these parameters can already be defined because they are fixed through external influences. First, in general, the auction will be a procurement auction involving more than one buyer (different network operators) with more than one seller. We determined that the auctioneer will be the separate network operators themselves or a (regulated) consortium, comparable to the European TSO consortium of the balancing power markets. Technical access criteria that respect, for example, terms of effectiveness and reliability are also important.

We extended the organizational aspects with several parameters that respect special requirements of regional flexibility markets. The first is the possibility of coordination between different network operators. Strongly connected with this parameter is the definition of the market (sub)areas for specific regional flexibility markets. A small market area could reduce the amount of relevant demanders (but perhaps also suppliers), while a larger market area generally leads to a better liquidity but also a larger effort of coordination. Furthermore, the coordination with other energy markets must be considered. These can be energy-only markets, balancing power markets or even other regional flexibility markets (which leads back to the coordination between different network operators).

The aspects that reflect special requirements of regional flexibility markets are difficult to define, but must be taken into account when designing the other parameters of the auction. Thus, they represent an expansion of classical auction theory to apply specifically to regional flexibility markets.

4.2. Goods

The parameters grouped under “goods” are of a descriptive nature. The parameters are the amount of goods (“How many different products are traded?”), the number of pieces of one good (“Is one good divisible or expandable?”) and the attributes (“What attributes additional to quantity and price exist?”) that describe goods (Buer, 2012). These parameters are determined with the chosen product design (see section 5).

One aspect that has already been described is the existence of a network structure for the traded goods (Buer, 2012). The network structure is physically determined by the electrical network and follows its physical rules. This aspect must be respected in the product design as well as in the design of the bidding process and winner determination.

4.3. Bids

The structure of the bids in the auction can be defined based on the characteristics of the organization and the goods. The fundamental structure of the bidding process was already named in the organizational parameter, structure of the bidding process. The parameters of bidding language (Buer, 2012; Nisan, 2000) and bidding rules (Buer, 2012; Wurman et al., 2001) give the space to define the activities of bidding in detail. These more abstract parameters have a wide range of potential designs themselves and answer the questions:

- What information does one bid contain and in which form is it submitted?
- Who can place, change and delete bids, and when?

In this context, an important parameter is the definition of relevant criteria (Buer, 2012). These are a sub-quantity of the number of attributes of the traded good and describe which attributes

are relevant for the bidding and winner determination processes. As mentioned, in the simplest setting these are the amount of a good and a price.

We will discuss the bidding rules, especially the temporal aspects, in more detail in Section 5.

4.4. Winner determination

The final task of designing an auction is the solution of the winner determination problem. The winner determination describes how the supply and demand sides are combined with a matching algorithm (Wurman et al., 2001), sometimes also called a scoring rule, that leads to the most efficient market result. The formulation of the winner determination problem leads to an optimization problem of the overall utility of participants (see, for example, Dauer, 2016) and is dependent on the product parameters and the bidding process in detail. With defined constraints, the solution of this problem can be restricted (e.g., with maximum prices or amount of bids accepted) (Buer, 2012).

In the context of regional flexibility markets and the previously mentioned network structure and technical restrictions, we state that the matching algorithm is a partly technical problem that leads to a techno-economical optimization. In other words, the winner determination will take into account not only the price of one bid but also technical properties, mainly the location in the physical network.

The final parameter of the winner determination is the pricing rule (Buer, 2012). This parameter can describe whether there is a price differentiation between the accepted offers (uniform pricing or discriminatory pricing), and can also define the pricing mechanisms for special auction formats (e.g., continuous trading, auctions with more than one round).

4.5. Summary of auction design

In the field of auction design, there is a quasi-infinite design space with many different design parameters. Some of these parameters can be determined with respect to the requirements of regional flexibility markets. Some organizational aspects can be stated, but the local aspect of the goods and consequentially the bids and winner determination are also important. The other parameters to be designed are more or less arbitrary. The temporal aspects of bidding are often associated with the product design and therefore will be discussed in the next section. Because of their general importance, different bidding rule characteristics will also be discussed in Section 6.

5. Design space of flexibility products

5.1. Overview

Basically, an electric flexibility product can be described as a defined way of producing or consuming electrical energy. On this abstracted level, there is no difference between a flexibility product and the products of other electricity markets within the energy system. These include the wholesale market, the balancing market and the retail market. All of these markets are handling more or less the same technical good (electric power per time, which can be simplified as electric energy); however, the accompanying product characteristics differ according to the individual requirements for using the electrical energy of the market participants. The differentiation of products can therefore be interpreted as one possibility to express the preferences of the market participants (Woo et al. 2014).

In the literature, the design of electrical products is often investigated from a consumer's point of view. Flath et al. (2015) and Woo et al. (2014) analyzed approaches of electricity product

differentiation. [Woo et al. \(2014\)](#) associated the possibility of different product specifications with the existence of supporting technologies, especially advanced metering technologies. With an increasing digitalization of metering and the possibility of two-way communication, the discussed possible electricity products have a higher potential to support the network and the energy system as a whole.

The product differentiation for consumers illustrates that a product design must primarily respect the needs of the product user. In this context, the first step toward a product design for a regional flexibility market is to define the main user of the product. As shown in Section 3, network operators can be named as the demanders and thus the main users of flexibility products. Nevertheless, the perspectives of both the network operators and the flexibility providers are important to develop a suitable product design.

To the best of our knowledge, there is no metric for the standardization of electricity product design, particularly in the context of flexibility. Therefore, we provide our own structure developed with respect to different studies in connection with flexibility products and markets (e.g., [Villar et al., 2018](#); [Dauer, 2016](#); [European Distribution System Operators for Smart Grids, 2018](#); [Ding et al., 2013](#); [Zhang et al., 2013](#); [Heussen et al., 2013](#)). Figure 2 summarizes this metric.

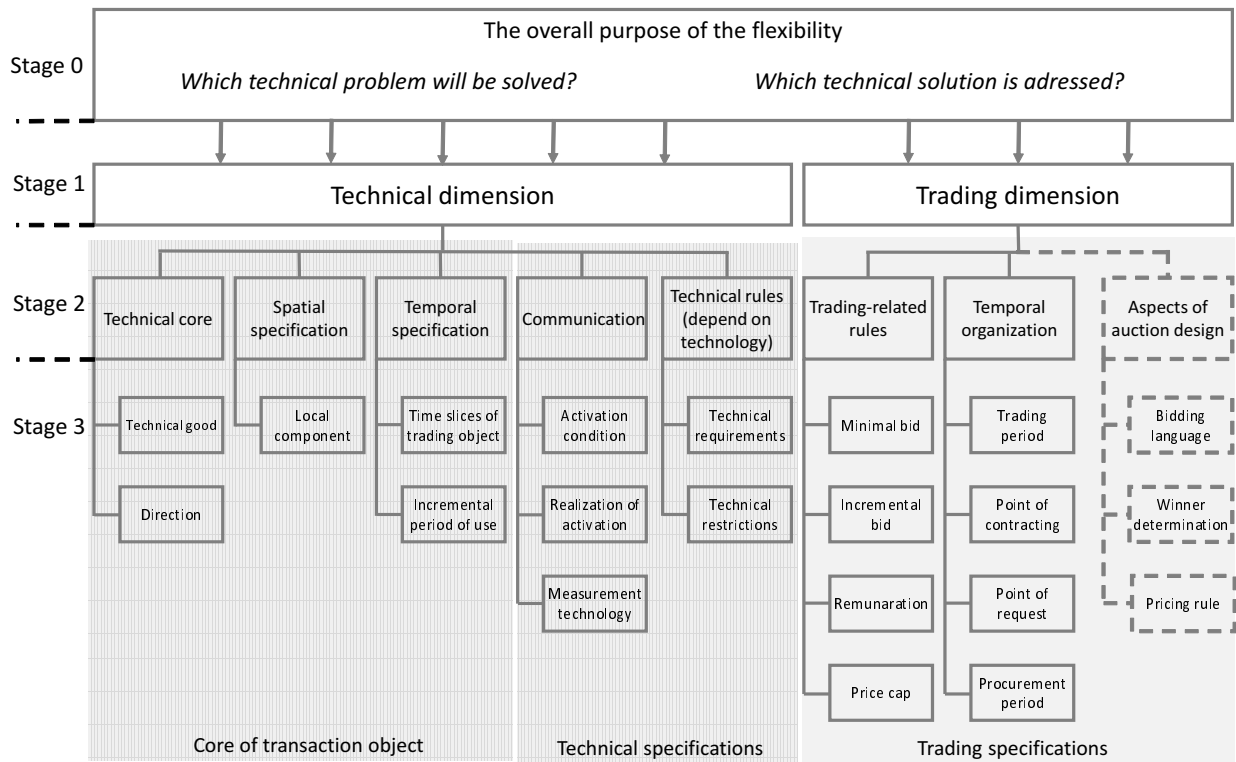


Figure 2: The developed metric summarizing the design of flexibility products

The metric is structured in four stages with different degrees of abstraction. Stage 0 addresses the overall purpose of the flexibility on which every design decision is fundamentally based. Stage 1 divides the design problem into a technical and a trading dimension. Stage 2 contains categories that group related product parameters. The product parameters of Stage 3 are the most detailed characteristic of the design space. The core of the transaction object contains three categories of

parameters: the technical core, the spatial specification and the temporal specification. With these parameters, the fundament of a tradable flexibility product can be defined. The other parameters complement this fundament with technical specifications and the specification of the trading process.

5.2. The purpose of the flexibility

As discussed at the beginning of this section, the fundamental question when talking about an energy product specification is: Who uses this product, and with what motivation? The purpose of the flexibility, therefore, is the reason for the existence of a product specification. In this context, two questions must be answered before designing the flexibility product in detail. First, which technical problem will be solved? As discussed in Section 3, the general objective of a regional flexibility market is the provision of network supporting ancillary services to the network operator. Therefore, the purpose of a flexibility product can be one of the ancillary services: congestion management, voltage control (see also [Ding et al., 2013](#)), redundancy support or a combination of these. Based on this, the second question to be answered is: Which technical solution is addressed with a specific product specification (henceforth referred to as designated technology)? In many cases, different technologies must be respected with different technical rules in order to avoid the discrimination of some of these technologies.

In summary, the purpose of the flexibility describes, on one hand, the aim of a network operator that wants to procure this special product; on the other hand, it takes into account the technologies that are addressed by the product specification. Thus, the purpose of the flexibility can be the same for different product specifications, but with different designated technologies and vice versa.

5.3. Technical dimension

The technical description of a flexibility product is of outstanding importance for two points of view: that of the network operator, which needs to evaluate the technical value of a flexibility; and that of the potential supplier, which needs information about whether his assets can technically provide the flexibility and how this can be quantified.

5.3.1. Technical core product

The first parameter of the technical core product is the technical good, which includes a physical value and a quantity. Classically, these can be an amount of power, but can also include other physical values, such as reactive power or even a change of voltage.

The direction of the technical good can, in most cases, be positive or negative. In relation to power, positive typically refers to production of power, and negative refers to consumption of power. Other technical goods, such as reactive power, have similar directions.

5.3.2. Spatial specification

The local component is the most significant difference between classical energy products in zonal energy markets and flexibility products. For the technical problems that are to be solved by the flexibility, the local relationship between demand and supply in general is quite relevant. Therefore, this information is a relevant product parameter for both the demand for flexibility and the offer.

5.3.3. Temporal specification

The temporal specification of a flexibility product contains two different time spans. First, the time slices of the trading object define the blocks of time in which the product can be traded. Based on this, the incremental period of use describes the shortest time step the flexibility can be delivered. Often, the incremental period of use and the time slices describe the same time span. In these cases, the product describes a flexible behavior in a specific time span. If the incremental period of use is only part of the time slices, the product can be interpreted as the option of a flexible behavior (over the incremental period of use) in a specific time span (the time slices).

5.3.4. Communication

The communication of a flexible product contains different aspects. The first is the activation condition. A flexible product can be activated as a direct request with a defined value of the technical good, or indirectly as a limit value or quota for a technical behavior (Ecofys and Fraunhofer IWES, 2017). This distinction respects, for example, the stochastic behavior of some smaller-scaled technologies. If the aggregation of many of these units is not possible, the reliability of a provided technical good decreases. In such cases, the amount of the technical good symbolizes a limit value and not the exact technical value; therefore, it is more difficult to quantify. The next important parameter is the technical realization of activation, including the description of a data format and signal transmission. The basic models of the realization of activation are a direct control of the flexible asset by the network operator or a control by the supplier in reaction to the request. Attributes that describe the proof of performance of a flexibility can be the measurement technology needed, including a baseline methodology (European Distribution System Operators for Smart Grids, 2018). These attributes are important to enable a standardized settlement for provided flexibility.

5.3.5. Technical rules

The technical rules of product design respect the point of view of a potential flexibility supplier and give the opportunity to define technical requirements but also technical restrictions of the application of individual units (European Distribution System Operators for Smart Grids, 2018; Ding et al., 2013). These two design parameters have many design options that can, but do not have to be, defined.

Selected examples for technical requirements of the network operator can be a reaction period that defines the time between the activation signal of the DSO and the beginning of the adaptation of the technical good, and a ramping period that describes the time needed to achieve the nominal value of the technical good. Both can be summed up to a minimum full activation period. In addition, quality requirements can be defined that include the maximum differences between the nominal value of the technical good and the effective value with respect to normal physical fluctuation, or other issues of technical quality.

An example of reasonable technical restrictions is an activation frequency that describes the maximum of activations in a single time slice. This is related to the recovery time as the minimum time between two activations and the minimum time of one request. In addition, minimal or maximal amounts of requests in specific time spans can be defined.

5.4. Trading dimension

5.4.1. Trading-related rules

The trading-related rules parametrize the technical product in the context of trading and define aspects of the payment. Trading-related and technical rules are strongly interconnected and therefore define the overlap between the technical and the trading dimensions.

The minimum bid is the minimal amount of a technical good that a demand as well as an offer can contain. In combination with the incremental bid, which is the minimum step between two different bids, the possibilities of the quantification of a technical good can be described.

Another important attribute is the remuneration, which basically defines what a flexibility is paid for. This could be a price per power, per energy or another reference such as the number of activations. A price cap can limit the value of the remuneration per bid. The remuneration is strongly connected with the auction design parameter of the pricing rule.

5.4.2. Temporal organization

The temporal organization of a flexibility product contains information about the structure of the trading process as well as the relationship between contracting and activation of a flexibility.

The trading period describes the time in which bidders can place offers (or demand) on the market. For example, the trading period could be a day-ahead auction, but could also be a continuous trading period that ends in defined points (e.g., 15 minutes before delivery). The point of contracting defines when the trade of the product is executed. For example, this could be any time in a continuous trading period or at the end of an auction. The point of flexibility request defines when the network operator, as the demander, activates the procured flexibility. Clearly, the points of contracting and flexibility request can be the same. If not, the trade contains an option for the network operator to request the procured flexibility at a later point. In such cases, the temporal specification of the product (time slices and incremental period of use) differ.

The procurement period defines the period of time the traded products refer to (e.g., years, days, hours, quarter-hours).

5.4.3. Aspects of auction design

As discussed in Section 3, the topics of auction design and product design are strongly associated. Therefore, a consistent separation between auction design and product design parameters is not possible. We identified four topics of auction design that are essential for a consistent definition of a product specification.

The temporal organization can be interpreted as auction aspects, which were considered in different parameters in Section 5.4.2.

The bidding language defines when and how bids can be replaced, changed or deleted. As discussed in Section 4.3, this parameter has a wide design space. The bidding language completes the ruleset in questions where technical and trading related rules may not provide an answer.

The winner determination describes the optimization problem that leads to the most efficient market outcome. This optimization must respect the technical parameters of the core product, the technical restrictions, but also the economic aspect of remuneration. Therefore, it is, in general, a techno-economic optimization. The detailed description of how to solve this optimization problem must be answered with optimization theory.

The pricing rule describes the remuneration that must be paid for a contracted trade.

5.5. Conclusion of product design

The provided metric of flexibility product design covers all parameters necessary to enable the description of tradable flexibility products with the relevant aspects of auction design. Nevertheless, other contractual aspects could be defined that complement the product design. The design space of these aspects is almost infinite, because it can contain any additional agreement between the network operator and flexibility supplier that is legal and seems useful for one or both parties. In the following section, we will show the suitability of our metric by applying it to different examples of flexibility products.

6. Exemplary product designs of flexibility products

In this section, we used the presented metric for the design space of flexibility products to compare the different approaches of current research projects of the German SINTEG program (Federal Ministry for Economic Affairs and Energy, 2019). In three different research projects, we identified five relevant flexibility market concepts and nine different products. Although some approaches come from the same project, all of them differ in some design details and method of implementation. Based on this standardized description, we are able to show similarities and differences and identify the general direction of current research in Germany.

The information in this section is based on publicly available data¹ as well as interviews² with experts involved in each project. Because all projects are not yet completed and reported, there is a lag of official data, and the presented findings must be interpreted as interim results.

6.1. Flexibility product approaches

Tables 1 and 2 show the application of the metric to the nine different products. The header of the tables includes the name of the market approach as well as a summarizing product name. We describe the characteristics of each of the 23 parameters of the metric, including the superior questions, for each product specification. Because of their text-intensive description, we have summarized some selected aspects of every market approach in the text below.

Selected aspects of ALF

Offers for short-term flexibility contracts contain a baseline and the possible flexible power for each quarter hour and can be placed until 16.00 day ahead. The second product, long-term flexibility contracts, are designed for flexible assets without a schedule, such as heat pumps and other electric heating systems, small photovoltaic power plants, electric vehicle charging points and others. These products can be contracted any time for an indefinite period, but the availability of a flexible asset can be activated and deactivated. Offers of both product types can optionally contain the following technical restrictions: the maximum number of requests per day, the maximum time of requests per day, the minimum time between two requests and the maximum time of one request. For short-term flexibility, the divisibility of the amount of offered power is also optional. (Zeiselmaier, 2019)

¹See, for example, www.csells.net (Smart Grids-Plattform Baden-Württemberg e.V., 2019), www.project-enera.de (EWE AG, 2019), www.windnode.de (WindNODE-Projektmanagement, 2018), as well as Zeiselmaier et al. (2018), EPEX SPOT SE (2018); 50Hertz Transmission GmbH (2019).

²Interviews with: Rinck (enera), 30.04.2019 ; Schutz (Comax), 16.05.2019 ; Meyer-Braune (WindNODE), 17.05.2019; Fieseler (ReFlex), 20.05.2019; Zeiselmaier (ALF), 21.05.2019.

Table 1: Comparison of exemplary flexibility products (I/II)

Market approach name		ALF	ALF	Comax	enera	enera	ReFlex	ReFlex	WindNODE	WindNODE
Product name		Long-term contracts	Short-term contracts	Flexible Power	Renewables	Non-renewables	Flexible Power	Quota	Day-ahead Flexibility	Intraday Flexibility
Superior questions	Technical problem	DSO's congestion management	DSO's congestion management	TSOs' (and DSOs') congestion management	Solution of vertical congestions caused by too much wind feed		DSO's congestion management and voltage control	DSO's congestion management and voltage control	TSOs' and DSOs' congestion management	
	Designated type of flexible asset	Small flexible assets	Controllable flexible asset	Controllable flexible asset	Renewable energy plant	Other flexible consumption or production asset	Controllable flexible asset	Renewable plant or electric vehicle charging point	Controllable flexible asset	
Technical dimension	Technical core product	Technical good	Electrical power	Electrical power	Electrical power	Electrical power	Electrical power	Electrical power	Electrical power	
		Direction	Positive or negative	Positive or negative	Positive or negative	Positive or negative	Positive or negative	Maximal production or consumption	Positive or negative	
Technical dimension	Spatial product aspects	Local component	Network node (low voltage or higher)	Network node (ultra-high voltage or lower)	Market area based on network topology		Network node (low voltage or higher)	Network node (low voltage or higher)	Network node	
		Time slices of trading object	None (continuous product)	Quarter-hours (composed to any desired blocks)	Quarter-hours and hours		Hours	Hours	Quarter-hours	
Technical dimension	Temporal product aspects	Incremental period of use (delivery)	Quarter-hours (= time slices of short term flexibility)	Subset of the offered time slices	Time slices		Time slices	Time slices	Subset of the offered time slices	
		Activation condition (quantifiability)	Direct (exact technical value)	Direct (exact technical value)	Direct (exact technical value)	Supplier responsible for activation	Supplier responsible for activation	Supplier responsible for activation	Supplier responsible for activation	Supplier responsible for activation
Technical dimension	Communication	Technical realization of activation	Activation from market platform via smart meter infrastructure	Supplier responsible for activation	Supplier responsible for activation	Supplier responsible for activation	Supplier responsible for activation	Supplier responsible for activation	Supplier responsible for activation	
		Measurement technology	Smart meter infrastructure	Existing infrastructure	Existing infrastructure	Existing infrastructure	Existing infrastructure	Existing infrastructure	Existing infrastructure	15-minute measurements (existing infrastructure)
Technical dimension	Technical rules	Technical requirements	Not (yet) defined	Not (yet) defined	Not (yet) defined	Not (yet) defined	Not (yet) defined	Not (yet) defined	Not (yet) defined	
		Technical restrictions	Optional technical restrictions	Not (yet) defined	Not (yet) defined	Not (yet) defined	Optional technical restrictions	Not (yet) defined	Optional technical restrictions	Option for dividibility of offered power

Table 2: Comparison of exemplary flexibility products (II/II)

Market approach name		ALF Long-term contracts	ALF Short-term contracts	Comax Flexible Power	enera Renewables	enera Non-renewables	ReFlex Flexible Power	ReFlex Quota	WindNODE Day-ahead Flexibility	WindNODE Intraday Flexibility
Trading rules	Minimal bid	Not necessary	Not (yet) defined	Not (yet) defined	100 kW	100 kW	Not (yet) defined	Not (yet) defined	100 kW	100 kW
	Incremental bid	Not necessary	Not (yet) defined	Not (yet) defined	100 kW	100 kW	Not (yet) defined	Not (yet) defined	100 kW	100 kW
	Price cap	Not necessary	Not (yet) defined	Not (yet) defined	Plus/minus 9999	Plus 9999/minus 50	Not (yet) defined	Not (yet) defined	Not (yet) defined	Not (yet) defined
	Remuneration	Flat fee	€/kWh	€/MWh	€/MWh	€/MWh	€/kW and €/kWh	€/MWh	€/MWh	€/MWh
Temporal organization	Trading period	Any time	Collecting of bids until 16.00 day-ahead	14.30 day-ahead until 15 minutes before delivery	Continuous trading until 5 minutes before delivery	Continuous trading until 5 minutes before delivery	Day-ahead auction between 14.00 and 15.00	Day-ahead auction between 14.00 and 15.00	Until 16.00 day-ahead	Until 2 h before delivery
	Point of contracting	Registration of suitable flexible asset	Subsequent to the end of the trading period	Any time during the trading period	Any time during the trading period	Any time during the trading period	Subsequent to the auction	Subsequent to the auction	Day-ahead until 22.00	Until 1 h before delivery
	Point of request	Point of contracting for short term flexibility	Point of contracting	Point of contracting	Point of contracting	Point of contracting	2 h before delivery	2 h before delivery	Point of contracting	Point of contracting
	Procurement period	Long term	Next day	Next/current day	Current day (intra-day)	Current day (intra-day)	The next day	The next day	Next day	1 h of current day
Aspects of auction design	Pricing rule	Regulated price	Pay-as-bid	Pay-as-bid with regulated price components	Pay-as-bid	Pay-as-bid	Pay-as-bid	Pay-as-bid	Pay-as-bid with regulated price components	Pay-as-bid with regulated price components
	Bidding rules	Detailed bidding rules defined	Detailed bidding rules defined	Detailed bidding rules defined	Detailed bidding rules defined	Detailed bidding rules defined	Detailed bidding rules defined	Detailed bidding rules defined	Detailed bidding rules defined	Detailed bidding rules defined
	Winner determination	Techno-economical optimization with consideration of technical constraints	Techno-economical optimization with consideration of technical constraints	Bottom up techno-economical optimization considering all offers, demands, sensitivities and limitations	Merit order in every market area	Merit order in every market area	Techno-economical optimization with technical network calculation	Techno-economical optimization with technical network calculation	Iterative techno-economical optimization process, beginning with the lowest DSOs and ending with the TSO	Iterative techno-economical optimization process, beginning with the lowest DSOs and ending with the TSO

Selected aspects of Comax

A flexibility offer contains a baseline and the possible positive or negative flexibility in each quarter hour. The first bid must be placed by 14.30 the day ahead and can then be changed until the bid is accepted or the trading period ends (at least 15 minutes before delivery). Each offer is divisible. Therefore, the contract can contain a subset of the offered quarter hours or a partial amount of the offered power. If a bid is accepted only partly, the rest of the bid is deleted. The supplier of this bid can replace the remaining (future) parts of the bid in order to be accepted for a future time slice. (Schutz, 2019)

Selected aspects of enera

Each bid is based on a reference baseline and belongs to a quarter hour or one hour. There are no additional possibilities for combinatorial bidding, such as block bids. Based on the basic product structure, there are two different product specifications: flexibility out of renewable energy sources and flexibility out of non-renewable assets. (Rinck, 2019)

Selected aspects of ReFlex

The trading is organized in a day-ahead auction from 14.00 to 15.00, where bids for the different products can be privately placed, changed or deleted. Each bid belongs to one hour of the next day. Bids cannot be placed as block bids (over more than one hour), but as optional bids (different optional bids for one hour). In addition, two technical restrictions are optional: the maximum number of connected time slices and the minimum time between two requests. Additional technical rules, such as maximum activation frequency or maximum hours of availability, are also under discussion. One accepted bid leads to a contractual option between DSO and the supplier. The supplier ensures that he can deliver the demanded flexibility. (Fieseler, 2019)

Selected aspects of WindNODE

Bids for the day-ahead product must be placed by 16.00 the day ahead and are contracted at 22.00 the day ahead. These bids contain a baseline for the next day and the flexible potential for at least four connected quarter hours. Bids for the intraday product can be placed until two hours before delivery and are contracted one hour before delivery. They contain the four quarter hours of one hour. The divisibility of bids can be chosen as an optional technical restriction. (Meyer-Braune, 2019)

6.2. Comparison of flexibility product design

Through the direct comparison of the product specifications, some common features and differences can be identified:

- All of the market approaches except one contain two different product specifications in order to address different types of flexible assets or different time horizons.
- All products are based on electrical power. Most use a direct value as the activation condition.
- The winner determination is a techno-economic optimization problem. The exact realization of solving this problem differs in detail.

- Most approaches address predictable (scheduled) flexible assets. Only two of the nine product specifications (long-term contracts [ALF] and quota [ReFlex]) address smaller assets with a more stochastic availability.
- The approaches use different strategies of realizing a short-term adaption of flexibility. These strategies contain different forms of short-term (intraday) trading options or the possibility of optional request of a contracted flexibility.
- Nevertheless, the temporal organization differs in all of the approaches.
- The technical rules are, in many cases, not yet defined. The same can be stated about the trading rules.

With the provided metric, the comparison of flexibility product design can be completed at a high level of detail. Based on this, in combination with results of the field tests of each approach, future work can evaluate the different specifications and identify best and worst practices. These interim results indicate the importance of the temporal organization, as all of the considered products differ in this specification. There is a lack of technical and trading-related rules, that may be due to the prototypical nature of the product approaches.

7. Conclusions and policy implications

The present paper contributes to the current debate about flexibility markets as one option for the procurement of ancillary services for the network operator. We have analyzed the technical background of using flexibility from the point of view of network operators as demanders as well as flexibility providers, leading to basic requirements that must be addressed when designing a flexibility market. These requirements include the existence of well-defined market rules and communication standards, including a consistent product design. This enables both sides of the market to value the possibility of trading flexibility, particularly in terms of technical feasibility and the reliability of offers.

We have also discussed relevant aspects of auction design: organization, traded goods, issues related to bidding and winner determination. The combination of technical aspects and aspects of auction theory led to the development of our metric, which includes 23 parameters and four stages that bring them into a consistent structure. To the best of our knowledge, we are the first to develop a holistic metric for the product design of flexibility markets.

Furthermore, by presenting and discussing five flexibility market approaches in Germany, we have provided a detailed overview of state-of-the-art research for future flexibility markets in Germany. The application of our metric shows that it is appropriate for a consistent description of flexibility products for network support in zonal energy systems.

The developed metric is a powerful instrument for the structured analysis and assessment of the vast diversity of approaches to flexibility markets and products. As seen by its application to the research projects described here (as well as other projects in the field of flexibility markets), this metric enables a structured comparison to be made at a high level of detail, and best practices can be identified in future work. Thus, this metric empowers national and international policy makers and practitioners in developing and assessing flexibility markets holistically, and therefore helps to simplify the implementation of best-practice solutions.

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Appendix – Detailed description of the considered market approaches

ALF

The ‘Flexibility Market of Altdorf’ (ALF) is designed mainly from the perspective of DSOs and therefore aims to solve congestions primary on the lower voltage levels. The technical product is in every case a direct electrical power that can be positive or negative and is related to the network node of the connection point. Based on this primal product structure there are two different product specifications with respect to the contractual time horizon. The first is a short term flexibility product. Offers for this product contain a baseline and the possible flexible power for each quarter hour and can be placed until 16.00 day ahead. The second product, long term contracts, are designed for flexible assets without a schedule, such as heat pumps and other electric heating systems, small PV plants, electric vehicle charging points and others. These products can get contracted any time for an indefinite period, but the availability of a flexible asset can get activated and deactivated. Offers of both product types can contain the following technical restrictions: a maximum number of requests per day, the maximum time of requests per day, the minimum time between two requests and the maximum time of one request. For short term flexibility also the divisibility of the amount of offered power is optional. The determination of the flexibility request follows a techno-economic optimization, considering the flexibility potential of both product types, costs (prices), sensitivities and limitations of the network. For a requested short term flexibility the supplier of this offer is responsible for the adaption of the schedule, for long term contracted assets the activation of the flexibility is realized from the market platform itself with the direct control via the smart meter infrastructure. The remuneration of short term flexibility products is a price per energy that is paid as bid. Long term contracts get a regulated flat fee. (Zeiselmaier, 2019; Estermann et al., 2019; Zeiselmaier et al., 2018)

Comax

The flexibility market ‘Comax’ has the aim to solve TSOs’ and DSOs’ power congestions. Therefore, the technical product traded on the market is a direct electrical power that can be positive or negative and is related to at least one network node in the ultra high voltage and in the voltage level of the connection point. A flexibility offer contains a baseline and the possible positive or negative flexibility in each quarter hour. The first bid has to be placed until 14.30 day-ahead and then can be changed until the bid is accepted or the trading period ends which is at least 15 minutes before delivery. Each offer is divisible, therefore the contract can contain a subset of the offered quarter hours or a partial amount of the offered power. The winner determination is a bottom up techno-economical optimization, considering all offers, demands and limitations of the various network operators. The acceptance of one bid results in the adaption of the schedule of the flexibility supplier, which has to be realized by the supplier himself. If the concerned bid is only accepted party, the rest of the bid gets deleted. The supplier of this bid can replace the remaining (future) parts of the bid in order to get accepted again later. The remuneration of the flexibility is a price per delivered energy (which can be positive or negative), while the pricing rule is pay-as-bid. It is planned to regulate some of the price components to avoid gaming problems. The settlement process is based on existing standards. The remaining parameters, like additional technical or trading related rules are not (yet) defined. (Schutz, 2019)

enera

The ‘Enera’ market is inspired by the wholesale intraday trading process of the EPEX SPOT. It primary got designed to solve DSOs’ vertical congestions, for example caused by too much wind feed in, but it also can be used to manage TSOs’ horizontal congestions. The basic technical good traded on ‘Enera’ is a direct adaption of electrical power that can be positive or negative. The trading process is organized in market areas, which are regions, based on the local network topology, where every node has the same sensitivity to possible congestion points. Market areas can be organized hierarchical, so that one market can be a sub area of another. Bids can be placed, changed or deleted during the trading period, which is organized as continuous trading until 5 minutes before delivery. Each bid is based on a reference baseline and belongs to a quarter hour or one hour. There are no additional possibilities for combinatorial bidding, such as block bids. Based on the primal product structure there are two different product specifications: the first is flexibility out of renewable energy sources, the second is flexibility out of non-renewable assets. The winner determination of the ‘Enera’ market is based on order books for each of the two products in each market area. Therefore, the trading follows a merit order. If a bid gets contracted the supplier of flexibility has the responsibility to adapt his baseline. The remuneration of an accepted bid is a price per energy that is paid as bid. There are bidding related rules that are mostly inspired by the rules of the wholesale intraday trading, e.g. a minimal bid and incremental bid of 100 kW and a price cap of plus/minus 9999 €/MWh. One exception is the lower price cap for non-renewable products, which is - 50 €/MWh. It aims to limit the bids of non renewable flexibility (e.g. flexible demand that gets remunerated for a higher consumption). The settlement process is based on existing standards. Additional technical rules are not necessary. (Rinck, 2019)

ReFlex

The ‘ReFlex’ market is designed mostly from a DSO’s point of view and aims to solve DSOs’ (future) problems like power congestions but also voltage problems. It trades two basic products that handle electrical power in two different ways, namely direct as exact (positive or negative) technical value and indirect as quota of consumption or production. The electrical power product is designed for assets that can plan their production or consumption and therefore can ensure exact values for their flexible behavior. The quota product respects the fact that smaller and more stochastic assets like renewable power plants or electric vehicle charging points are not able to deliver plannable flexibility. Therefore, these assets can offer a limitation (quota). Both specifications are located in the network as exact as possible via the network connection node. The trading is organized in a day-ahead auction from 14.00 to 15.00, where bids for the different products, can be invisibly placed, changed or deleted. Each bid belongs to one hour of the next day. Bids cannot be placed as block bids (over more than one hour), but as optional bids (different optional bids for one hour). Also two technical restrictions are optional: maximum number connected time slices and minimum time between two requests. One accepted bid leads to a contractual option between DSO and supplier. The supplier ensures that he can deliver the demanded flexibility. The point of the flexibility request is two hours before the delivery and therefore in a shorter time range than the trading process itself. If one offer gets requested the supplier is responsible for adaptation of the schedule or the implementation of the limitation. The winner determination as well as the termination of the flexibility request is based on a techno-economical optimization containing an explicit technical network calculation. Because of the suppliers of flexibility have to ensure an optional service the remuneration must contain a price per power but also a price per energy. The pricing

rule is pay-as-bid, but price caps and regulations are under discussion. Additional technical rules such as maximum activation frequency or maximum hours of availability are also under discussion. The remaining parameters are not (yet) defined. (Fieseler, 2019)

WindNODE

The ‘WindNODE’ market place has the aim to solve TSOs’ and DSOs’ power congestions. Therefor the technical product traded on the market is a direct electrical power that can be positive or negative and is related to at least one network node in the maximum voltage (or lower). Based on this primal product structure there are two specifications relating to different time horizons. Bids for the day-ahead product have to be placed until 16.00 day-ahead and get contracted at 22.00 day-ahead. These bids contain a baseline for the next day and the flexible potential for at least four connected quarter hours. The second specification is the intraday product. Bids for this product can be placed until 2 hours for delivery and get contracted one hour before delivery. They contain the 4 quarter hours of one hour. As an optional technical restriction the divisibility of bids can be chosen. The winner determination is a techno-economical optimization process, beginning with the lowest DSOs and ending with the TSO. If a bid gets accepted the supplier is responsible to adapt his baseline. The remuneration is a price per energy. The pricing rule is pay-as-bid, but the regulation of price components is under discussion. The minimal and incremental bid is 100 kW. The amount of power can be divisible or indivisible. The settlement process is based on existing standards. (Meyer-Braune, 2019)