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The search for the perfect match: Aligning power-trading products to the energy transition☆

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ABSTRACT

Given the growing share of uncertain renewable energy production, the energy transition challenges modern power systems and especially calls for increased flexibility. However, relevant information on the highly asset-specific flexibility potential is typically only known to plant operators themselves and not, e.g., to transmission system operators. Therefore, liberalized electricity markets use prices that set explicit monetary incentives to disclose the relevant private information about the market participants' assets. In this way, information asymmetries may be reduced. Given the different challenges of an integration of renewables, we argue that the associated new forms of volatile power profiles require new forms of power-trading products. In particular, based on recent advances in technical power measurement and billing, individual and market participant-specific power profiles may be superior to the current trading of average volumes. Against this background, we first outline various evolutionary adjustments of existing power-trading products and their underlying product parameters including (1) strengthening local pricing, (2) finer temporal granularity, (3) smaller minimum volume, and (4) shorter gate-closure time. Second, we open up a new perspective in form of a more disruptive shift towards power-profile trade, where market participants define their trading product using the actual power profile as a new product parameter.

1. Introduction

In the past decades, most countries liberalized their wholesale electricity markets (Graf and Wozabal, 2013). For instance, Germany performed such a transformation in 1998 (Bower et al., 2001). In contrast to a traditional independent system operator (ISO) that centrally managed and controlled the entire power system as a kind of omniscient planner in the pre-liberalization era, information asymmetries typically imply that liberalized markets can realize an increased efficiency compared to a traditional centralized dispatch (Arentsen and Künneke, 1996). In particular, under imperfect information, the ISO and today its successors, the transmission system operators (TSOs), would not be able to determine the welfare-maximizing dispatch since they are missing crucial information on, e.g., the actual, highly individual technical characteristics of the available assets. The latter information is usually only known to the plant operators themselves. To tackle this general problem of information asymmetry, markets set explicit monetary incentives in form of market prices to disclose such relevant private information on the available assets using corresponding bids. Ultimately, the efficiency of the resulting dispatch may increase as compared to a centralized dispatch.

Given the general existence of information asymmetries, the current integration of renewable energies significantly increases the need for appropriate market structures to incentivize market participants to disclose their individual and asset-specific information. In particular, due to the highly fluctuating supply of renewable energies, flexibility gained growing importance (Kubli et al., 2018). In this context, flexibility refers to the general ability to respond to short-term and unexpected imbalances between supply and demand (Alizadeh et al.,

☆ The views and opinions expressed in this paper are those of the authors. Therefore, the paper does not necessarily reflect the official policy or position of the University of Bayreuth, the Fraunhofer Institute, or EPEX Spot SE.

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2016; Doege et al., 2006; Ulbig and Andersson, 2015). To address the growing flexibility gap associated with the increasing share of renewables and the planned phase-out of conventional power plants, the length and gate-closure time of intraday market products were already shortened in many countries over the past years. For example, at EPEX SPOT,[1] currently either 15-min-, 30-min-, or 1-h-products can be traded at intraday continuous with a gate-closure time of 30 min before delivery.[2] These products aim at balancing deviations from the day-ahead schedules at short notice.

Notwithstanding these attempts on intraday markets to better balance demand and fluctuating supply, the current product design is still based on average power volumes that are contracted by the market participants. Thus, in contrast to self-designable products that are traded over-the-counter, products merchandised on the power exchange cannot be defined individually by the market participants and are instead specified by the power exchange operator itself. Trade of such standardized products typically ensured low transaction costs as well as corresponding power-consumption measurement and billing in an easy-to-implement fashion in the past.

On the grid level, the increasing share of renewables with their associated production intermittency yields a growing threat of grid instability. In particular, renewables are inherently characterized by specific power profiles like solar ramps, whose concrete shape depends on unknown weather conditions (Goutte and Vassilopoulos, 2019). These new power profiles result in rapid changes of residual load, which occur increasingly in the morning and evening hours. As power trading is still often organized on an hourly basis, corresponding challenges for grid operation due to frequency fluctuations occur daily and typically during hour changes as illustrated in Fig. 1 (Weissbach and Welfonder, 2009). Especially during such changes of the hour, large imbalances between the contracted average power and the actual power profile can be observed. The reason for such frequency deviations may - at least to some degree - lie in the described trading-product design, which is based on average power volumes. In contrast to currently standardized products on power exchanges, however, the technical assets typically have a high variety of different technical characteristics. Ultimately, this raises questions about an adequate future trading-product design of power exchanges.

To ensure an economically efficient and stable future power system in times of an increased renewable energies' feed-in and an associated growing flexibility demand, adjustments to existing power-trading products will be inevitably. Based on a general definition of current power-trading products and its main product parameters, in a first step we will therefore elaborate on four different evolutionary adjustments of existing power-trading products. As we aim at a general discussion of the product design, for most parts of the paper we relate to both intraday and day-ahead markets.[3] In particular, we will base our product evolution on the current European energy-only market, an unbundled, exchange-based market (Cramton, 2017; Wilson, 2002) – where the fundamental product is not the actual dispatch of an asset but nomination into a balancing group – and on the planned future market design set out by the Clean Energy for all Europeans Package (European Union, 2019). This implies that we do not consider other possible developments like, e.g., unit commitment. Ultimately, using the assumed market framework, our presented product evolution will rely on main existing product parameters that relate to (1) local pricing, (2) temporal granularity, (3) minimum volume, and (4) gate-closure time.

[1] Market region DE/LU.

[2] The gate-closure time was even reduced to 5 min before delivery within local TSO zones.

[3] To ensure clarity and readability, throughout the paper, we explicitly highlight exemptions where only one of the markets (intraday or day-ahead) is referred to.

Enabled by substantial advances in technologies for data collection and processing (e.g., smart meters to gather information from decentral consumers), in a second step we also highlight the need to change the current perspective of power-trading products and to bring trade much closer to the possible operating modes of power plants, including their underlying flexibility potentials. Given that the technical characteristics of assets are typically only known to the plant operator himself, we discuss a shift in power-trading products with market participants being able to define their own products in form of individualized power profiles. In order to trade such individual power profiles, it will be necessary to include the actual profile of power consumption or feed-in as a new parameter in the design of power products. Such a shift will also imply a change in current matching procedures on intraday continuous markets towards so-called cross-matching, i.e., the matching of multiple orders instead of current bilateral intraday trade. As we conclude, a consideration of this new perspective may ultimately contribute to a successful low carbon transformation of our energy system via a broader deployment and development of the different flexibility options with a reduced curtailment of renewables. The latter is currently a severe problem, e.g., in Germany, due to the lack of sufficient flexibility sources that can balance the intermittent supply of renewables. In this context, also the necessary technical progress with corresponding flexibility innovations may positively be influenced by new revenue potentials that new power-trading products may possibly open up.

In literature, the discussion and analysis of power-trading products only started with the power market liberalization at the end of the last century (Arentsen and Künneke, 1996). Subsequently, the introduction of spot market power exchanges, e.g., EPEX SPOT in 2008, marked the beginning of the introductory phase for products traded at short notice (Viehmann, 2017). In literature, the fact that changes in power-trading products are necessary and unavoidable, especially in order to meet the requirements of future low-carbon power systems, only became evident in the last decade (Henriot and Glachant, 2013). Today, there already exist examples for necessary adjustments of individual parameters of power exchange products (Pechan, 2017), but to the best of our knowledge, current literature has not given an integrated view of a possible product parameter evolution, nor has addressed the issue of power-profile trade. Instead, we are the first to open up this new perspective, which is a main novelty of the paper.

This paper is organized as follows: In Section 2, we briefly introduce power exchange structures and give a definition of the currently standardized trading products. While we aim at a holistic description of power trade, for illustrative purposes, we will refer to EPEX SPOT as an example throughout the paper. Section 3 elaborates on evolutionary adjustments of trading products that may be seen as a short-run option for exchange operators (or regulators) to develop the currently available products. We then highlight, why a shift towards future power-profile trade may offer new perspectives and possibilities in times of the low-carbon energy system transformation. Finally, Section 5 draws main conclusions and summarizes the paper.

2. Status quo: current power-trading products and associated challenges

2.1. Defining trading products and orders

The main task of any exchange is to bridge the supply side and the demand side of a certain product. In particular, as an integral part of liberalized markets, exchanges match supply and demand as to maximize welfare (Golombek et al., 2013). In the case of power exchanges, these products are standardized contracts for the physical delivery of power within a given transmission system (EPEX SPOT SE, 2019b). More specifically, such products specify that (1) a certain contracted average power is traded between exchange members (2) at a specified time or trading interval, (3) at a certain price, and (4) in a

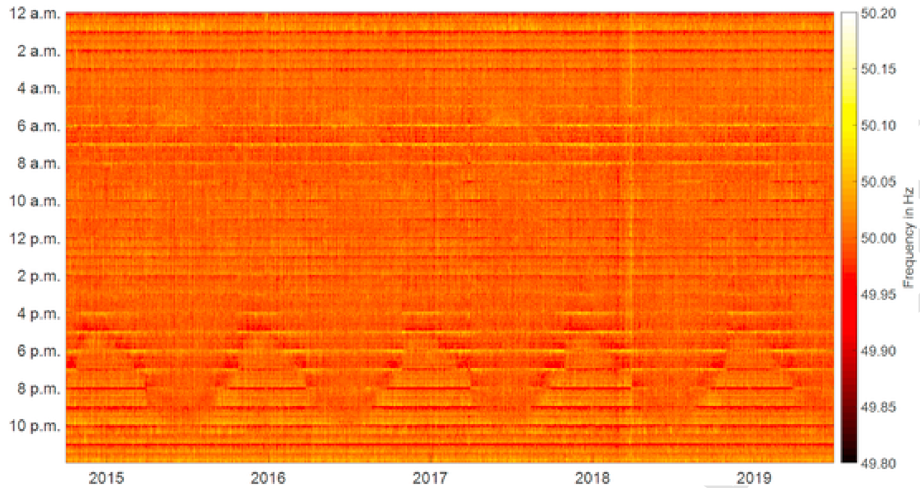

Fig. 1. Network Frequency in the European electricity grid. Source: Own figure. Data: (Réseau de transport d'électricité, 2019).

covered regional area. Such a definition of a power-trading product directly implies that the contracted average power in a trading period starting at time t with length Δ is completely independent of the actual power profile p that will be realized within $[t,\ t+\Delta]$, but only the average power q is specified in the respective contract:

$$q = \Delta^{-1} \int_{t}^{t+\Delta} p\left(t'\right) dt' \tag{1}$$

In other words, as no fixed power profile p is contracted, for instance each supplier can therefore choose its own actual power profile when operating its plant as long as the contracted average power amount q is not violated in the considered trading period (according to Equation (1)). Both the average quantity q and the corresponding price π typically have given upper and lower bounds (indicated by the two symbols '+' and '-') as specified by the power exchange:

$$q^{+} \geq q \geq q^{-} \text{ (volume bounds) } \pi^{+} \geq \pi \geq \pi^{-} \text{ (price bounds)}$$

In addition to the above standard products as defined by Equation (1) together with the corresponding volume and price bounds, also so-called blocks may be traded. Block products connect multiple expiries with at least two contiguous expiries on the same day of delivery. The unique feature of block products is that the involved individual products are only executed if all the individual products within the block can be matched. The number of blocks $n \in \mathbb{N}$ expresses the actual product type. $n = 1$ indicates the special case of a single product that combines a price and a quantity for an expiry and a covered regional area. However, also different pre-defined blocks with $n>1$ exist, e.g., baseload blocks (0–24 h) or peakload blocks (9–20 h). As Fig. 2 indicates, baseload blocks are supposed to cover the base load of one day, while peakload blocks and especially hourly products are rather used to satisfy the remaining daily demand pattern. In addition, exchange members are usually allowed to also define their own block, whereas hourly products and 15-min products may typically not be combined (EPEX SPOT SE, 2019a).

To give an example of how such standardized products may be designed by a power exchange, Table 1 summarizes current products that can be traded at EPEX SPOT.

In contrast to the definition of products and contracts, we speak of an order if exchange members select certain values for the "placeholders" in the standard contract and submit them to the power exchange. In its simplest case of $n = 1$, an order is just a chosen price-quantity combination submitted to the exchange for a defined period of time and a given regional area. The so-called gate-closure time, also known as the lead time, is defined as the time after which submitted orders of the market participants cannot be modified anymore. In other words, the gate-closure time describes the time period between the moment in which the order has to be submitted to the power exchange and the moment in which the power is actually delivered. Against this background, the gate-closure time directly determines the feasible trading periods t for which an order can be placed. Therefore, it is another important product parameter.

To further illustrate current trading, Fig. 3 gives three possible actual power profiles that can be realized with the same standard contract of 20 MWh (= contracted energy for 1 h calculated as the integral of power over time). For the chosen example, we use a consumer. However, we note that similar arguments also hold for the producer's perspective. In Fig. 3a), a power profile is depicted that refers to a constantly increasing amount of power from 0 MW to 40 MW, whereas in Fig. 3b) the consumed amount of power is constant 20 MW and therefore accurately reflects the contracted average quantity. Another feasible consumption pattern is described in Fig. 3c), where power is not consumed for most of the considered trading period. Instead, only in one-quarter of the considered trading period a short-term power peak of 80 MW appearsFig. 4.

The above example clearly highlights that under the current product design, the actual consumption of the contracted power can take various forms, as no concrete power profile is specified in the contract and only an average power consumption must be adhered to.[4] Ultimately, this may result in severe challenges for grid operation and grid stability that transmission system operators must tackle. Corresponding problems for grid operation can for instance be seen, if we assume that the contracted power of 20 MW must be transmitted to a consumer via an existing power cable with a capacity of 20 MW. Obviously, in such a case only under the actual power profile shown in Fig. 3b), the TSO does not need to intervene and downregulate the respective consumer.

2.2. Market clearing and auctioning

In order to match submitted orders, markets determine so-called equilibrium prices. Different spot-markets like the day-ahead or intra-

[4] Only the existing grid-fee system may in some countries incentivize participants to have a preferably constant power profile.

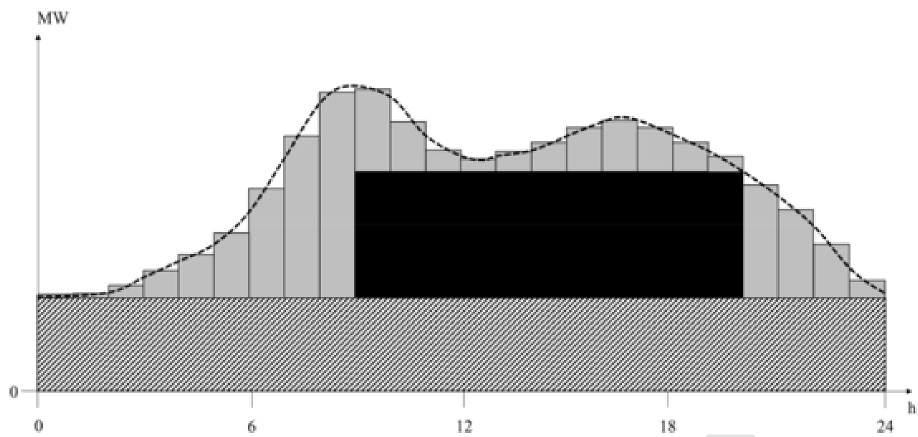

Fig. 2. An exemplary daily load profile (dashed line) satisfied by a baseload block (striped area), a peakload block (black area), and individual hourly products (grey areas). Source: Own figure.

day market may apply different auction forms and rules for the corresponding price formation. In general, especially in rather illiquid markets single-price auctions like in Spain are carried out several times a day after the submission and collection of intraday orders. Alternatives are pay-as-bid procedures (intraday continuous trade), which are, for instance, used in Germany. Under such an auction form, there is a 1-to-1 matching of orders of power suppliers and consumers, i.e., a single sell order is matched with a single buy order. Again, Table 1 gives examples for auction forms used at EPEX SPOT.

Different power market implementations may additionally vary, depending on how physical transmission constraints are accounted for in the market-clearing and to which degree corresponding market prices reflect the value/scarcity of power transmission (Weibelzahl, 2017). While in Germany a uniform pricing system is used, where physical transmission constraints are completely neglected, under nodal pricing all relevant physical restrictions are considered, and grid bottlenecks are priced appropriately (see also the literature in the next section). An intermediate form is the zonal pricing system, where only inter-zonal transmission constraints are taken into account and transmission bottlenecks are only imperfectly priced (Grimm et al., 2016a, 2016b).

3. Product evolution based on existing trading rules

Based on the description of current power-trading products in the previous section, we now elaborate on possible extensions and adjustments that may be implemented in the short-run by power exchanges (or regulators) to better align today's trading products to the needs of the energy system transformation. In particular, possible adjustments of current product characteristics and parameters shall aim at a better reflection of the real-world conditions relating to the current power production, transmission, or demand situation in the power system. Ultimately, flexibility potentials to deal with the intermittency caused by renewables shall be better exploited.

In the following, we will present four different options of how to develop current products. These options relate to the four product parameters of (1) local pricing, (2) temporal granularity, (3) minimum volumes, and (4) gate-closure times as introduced before. For each option, we will highlight main arguments for a corresponding product adjustment. However, we note that a comprehensive description and final evaluation of all the relevant effects is not possible within the scope of this perspective article. In particular, there may be complex trade-offs between different adjustments that will have to be further analyzed and adequately addressed in future work. For instance, a shorter gate-closure time will not necessarily result in a different dispatch for slow and inflexible assets, like nuclear or lignite plants.

In addition, let us also emphasize that while the product parameters (1), (2), and (3) apply to intraday continuous, intraday auction, and day-ahead auction, the product parameter (4) only refers to the intraday continuous market.

3.1. Strengthening local pricing

One possibility of adapting power-trading products is adding a new local trading component, e.g., in form of a split of existing price/control zones for which specific products can be traded. The underlying idea is to price grid bottlenecks more appropriately. In addition to existing nodal-pricing markets in the US, also in Europe corresponding pilot projects are already being implemented including enera in Germany, a SINTEG project. Original work relating to nodal pricing comprises, e.g., Bohn et al. (1984), Chao and Peck (1996), Hogan (1992) or Schweppe et al. (1988), while zonal pricing is for instance discussed in Bjørndal et al. (2003), Bjørndal and Jørnsten (2001), Burstedde (2012) or Oggioni and Smeers (2013).

A shift towards increased regional trade may be associated with a growth in the price volatility due to the decreased number of traders in the respective price or trading zone (Bertsch, 2015). Such an increase in the price volatility may create new incentives for an adequate flexibility supply and corresponding investments (Henriot and Glachant, 2013). However, not only within a zone, but also between different zones price differences may be observed, leading to trade possibly being shifted to price zones with higher market liquidity. Here, we refer to liquidity as the number of orders in the respective order book(s). Ultimately, adding a local component will generally imply a more efficient grid congestion prevention in form of a more efficient coordination and dispatch. By this, also the curtailment of power supply might be reduced, as the explicit consideration of grid bottlenecks may yield more efficient price signals that for instance incentivize flexible consumers to increase their consumption temporarily. Nevertheless, lower market liquidity of smaller price zones could lead to the threat of market power abuse and thus to distorted price signals (Kumar David and Wen, 2001).

3.2. Finer temporal granularity

A further adaptation of current trading products consists of finer granular products with shorter product lengths. In 2011, the shortening of the product length from 1 h to 15 min already yielded initial positive effects at EPEX SPOT in Germany, which helped to compensate for intra-hour volatility (Märkle-Huß et al., 2018; Remppis et al., 2015; Weissbach and Welfonder, 2009). By further shortening the product length, the congruence of power generation and consumption could be positively affected, creating additional incentives for corresponding flexibility providers (Märkle-Huß et al., 2018). In addition, as it may

Table 1
Overview EPEX SPOT products.

	Day-Ahead Auction	Intraday Auction	Intraday Continuous
Type of market	Blind auction	Blind auction	Continuous trading
Trading segment	Day-Ahead	Intraday	Intraday
Zones concerned	DE/AT	DE (all TSO zones)	DE
Product	1-h contract	15-min contract	1-h contract 30-min contract 15-min contract
Frequency	Daily from Monday to Sunday, year-round	Daily from Monday to Sunday, year-round	24 h a day from Monday to Sunday, year-round
Number of products	24 hourly products	96 quarters (excluding DST changes)	
Order book opening	Order books open 45 days before delivery	Order books open 45 days before delivery	One day before delivery at 15:00 (hourly products)/15:30 (30-min products)/16:00 (15-min products)
Order book closing	One day before delivery at 12:00	One day before delivery at 15:00	30 min before delivery 5 min before delivery in local TSOs areas (60 min before delivery in XBID)
Results publication time	As soon as possible from 12:42	As soon as possible from 15:15	
Block orders	Block orders (pre-defined blocks or user-defined blocks) (maximum volume for block order is 600 MW)	Block orders (pre-defined blocks or user-defined blocks) (maximum volume for block order is 50 MW)	Block orders (pre-defined blocks or user-defined blocks) (products whose trading session ends 5 min before delivery in local TSOs areas cannot be part of blocks)
Minimum price increment	0.1 €/MWh	0.1 €/MWh	0.1 €/MWh
Minimum volume increment	0.1 MW	0.1 MW	0.1 MW
Minimum and maximum price	-500€/MWh 3000€/MWh	-3000€/MWh 3000€/MWh	-9999.90€/MWh 9999.90€/MWh

Source: Own table on the basis of EPEX SPOT data.

be possible to resolve imbalances in the power system by a shorter product length, transmission system operators may save balance power (Koch and Hirth, 2019). For the balance responsible parties, shorter products may also simplify the balance and compensation of the balancing group in general. This, in turn, may ultimately contribute to a higher degree of balance group commitment. However, there may, at the same time again be a loss of liquidity due to the extension of the product range and the respective reduced number of orders in the order book(s).

3.3. Smaller minimum volume

In addition to the above evolutionary adjustments, smaller minimum trading volumes are another option to adapt existing power trading products in times of increasing renewable energies. In particular, a reduction in minimum trading volumes could lead to a further removal of current obstacles to access the power exchange for small market participants, as for instance the need for intermediaries (under the precondition of low transaction costs) would decrease (Klessmann et al., 2008). With the associated increase in the number of active market traders, the liquidity of the power exchange may consequently rise (Hagemann and Weber, 2013). Thus, an increase in the number of exchange members may move the market closer to a perfect competition market with a more diverse spectrum of consumers, producers, and prosumers. In addition, new revenue streams of small flexibility suppliers may have a generally positive effect on a decentralized flexibility provision and ultimately foster energy democracy (Burke and Stephens, 2017).

3.4. Shorter gate-closure time on intraday markets

For the case of intraday markets, another temporal aspect relates to a shorter gate-closure time. Since intermittent renewable energy sources have begun to penetrate the market significantly, a shorter gate-closure time may be seen as a requirement to better balance demand and supply deviations at short notice. Ultimately, there may in general be a quicker response time to imbalance situations with associated fluctuating prices that market participants face. Such shortenings of the gate-closure time are already implemented to some extent, in particular within control areas of TSOs in Germany. Obviously, market participants will generally be able to improve the quality of their forecasts of the expected actual power consumption or reduce the forecast error rate in cases where the latest possible trading point in time gets closer to the delivery point in time (Holttinen, 2005). As another result of a reduced gate-closure time, the corresponding short-term decisions of traders may lead to higher price spreads and may, therefore, create new incentives for flexibility supply. At the same time, there may again be a reduced need for balancing power (Barth et al., 2008; Hiroux and Saguan, 2010). Finally, a shortening of the gate-closure time towards real-time trade would partially lead to an overlap between intraday products and balancing power. This overlap may result in a partial market segment integration of the intraday and the balancing market (Rieß et al., 2017). Nord Pool already offers trading up to a few seconds before delivery, while EPEX SPOT offers trading within TSO zones up to 5 min before delivery.

4. The new perspective of power-trading products

Flexibility is typically highly asset-specific with the actual technical flexibility characteristics of an asset only being known to the plant operator himself. Against this background, this section discusses a change in power-trading products where market participants are able to define their own products in form of individualized power profiles. As power-profile trade gives up the standard paradigm of trading average quantities, we note that it goes beyond a pure product evolution. Given the assumed European market design, the proposed power-profile trade approach will, however, not question the current market framework, but it rather focuses on the introduction of a new product parameter. Nevertheless, a consistent and successful introduction of such a new product parameter will have implications for an efficient market design, which we will briefly highlight in Section 4.3 (specific implications for intraday continuous markets) and in Section 4.4 (general implications).

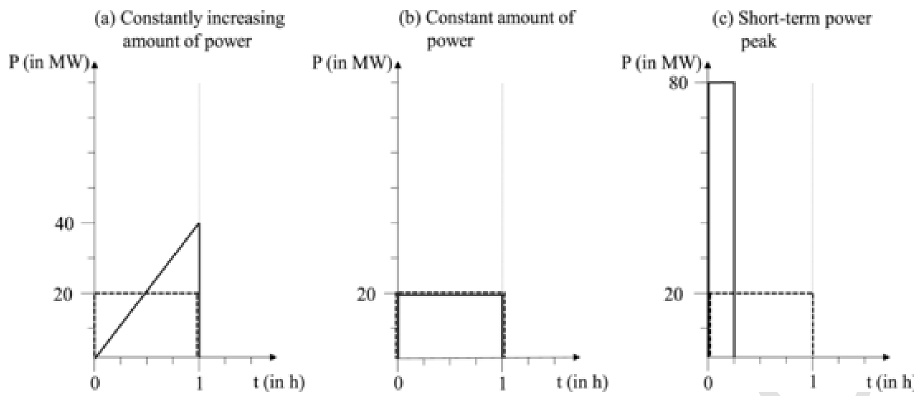

Fig. 3. Different power profiles for a contracted volume of 20 MWh. The black lines indicate the actual power profile, while the dashed lines indicate the contracted average power as the ration of the energy amount and time (1 h).Source: Own figure.

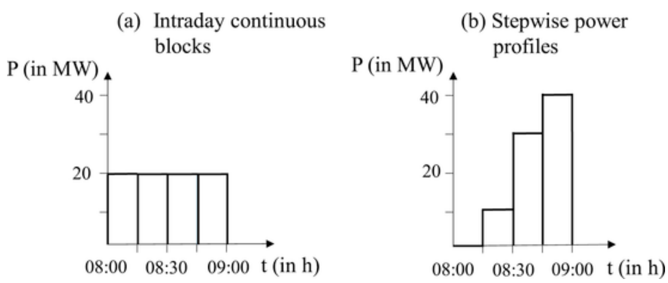

Fig. 4. Examples of block products.Source: Own figure.

For the ease of presentation, we will introduce the key aspects of the power-profile trade concept step-by-step (see Section 4.1 and Section 4.2) and relate to both day-ahead and intraday markets.

4.1. Introduction of stepwise-power profiles

As described in Section 2, blocks can already be traded on power exchanges like the EPEX SPOT, but each product of a block must typically be traded with the same average power. Such a situation is exemplarily illustrated in Figure 4a) for the case of an average power of 20 MW.

The first step towards profile trade comprises the introduction of stepwise power profiles for each trading period of the block according to Equation (1): Stepwise power profiles are functions *pt* where each single product *t* of a discrete block can have its own individually defined average power amount, but all of them are specified in a common contract. For instance, using stepwise profiles, it will be possible to trade a block that is contractually fixed at 0 MW for the first 15 min of an hour, 10 MW for the second 15 min, 30 MW for the third 15 min, and 40 MW for the fourth 15 min of an hour as depicted in Figure 4b). The latter figure may indicate part of a solar ramp, which is “completely” shown in Fig. 5. Depending on the actual weather conditions, similar ramps may also be observed for wind power plants. However, we note that wind power ramps are typically less steep with a shape that is not easy to predict ex ante.

4.2. Introduction of power as an explicit new product parameter

The second step towards power-profile trade explicitly relates to the contracted quantity *within* a given trading period. In the past, high transaction costs, limited power measurement possibilities, and corre-

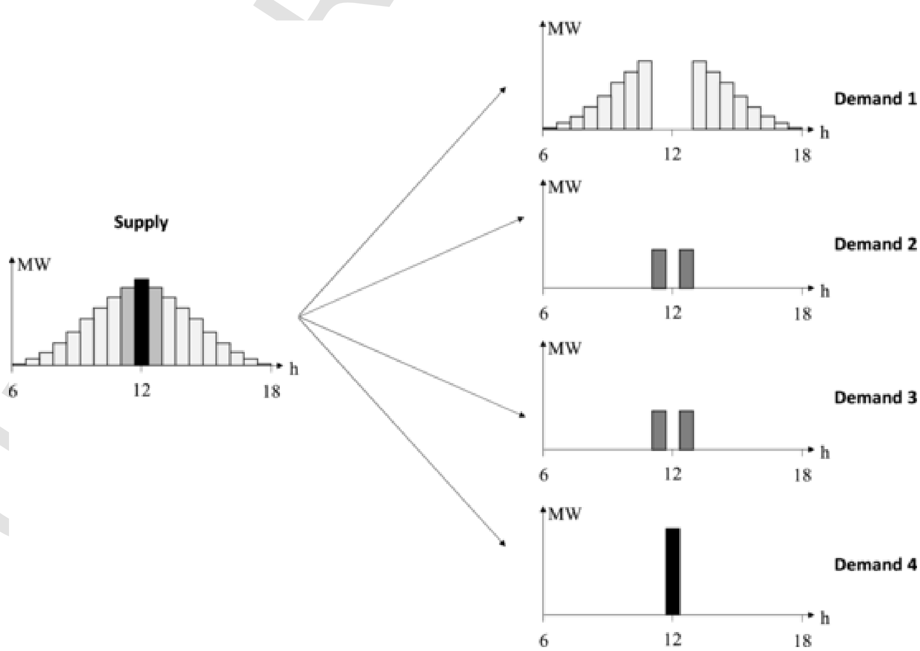

Fig. 5. Example of cross matching with a single seller and four buyers.Source: Own figure.

sponding billing required a high standardization of trading products. However, with the advent and the development of modern digital technologies, the latter barriers significantly declined. In particular, new instruments such as smart meters can collect and measure power consumption and generation on a fine granular basis (Doostizadeh and Ghasemi, 2012). Given these recent advances in digitalization-driven metering and billing, there is now the possibility to integrate the power p in Equation (1) as part of the product definition itself in order to better map the technical characteristics of PV systems, wind farms, and the various flexibility suppliers. Such profiles may for instance be determined by power generators on the basis of the technical characteristics of their plants. Therefore, with the second key step, we argue that trade may no longer exclusively base on the average energy quantity, but that an additional inclusion of the power profile p_t within a given trading period $[t, t + \Delta]$ may be beneficial dealing with increased fluctuations in the future power system.

With the knowledge of the underlying profile p_t, classical block structures develop into continuous profiles p. Given the latter, the implementation of the actual matching that requires a discretization into, e.g., hours, half-hours, or quarters, will not change the trader's bid, but it is just a technical characteristic of the respective trading system.

Thus, changes in the technical specifications and parameters of the traded products (e.g., a change in the time granularity) can be implemented without forcing the traders to change their bidding behavior. With respect to intraday markets, bidding a continuous profile, for instance, allows the trader to watch one order book, i.e., his own order book, instead of all "atomic" order books that correspond to the time-discretization dictated by the power exchange. Ultimately, trade may – especially for small traders with limited know-how in trading – become simpler and, therefore, possibly increase the number of active participants in a future decentralized electricity system.

4.3. Implications of power-profile trade for intraday continuous markets: introduction of cross matching

Implementing such a new trade of power profiles, it is increasingly unlikely that a 1-to-1 matching of orders, which is particularly used on intraday continuous markets, stays a future matching option. As a result, a more sophisticated matching process will be necessary.

In particular, as compared to day-ahead trade, where all orders flow into a pool and supply and demand are balanced using a single price, intraday continuous trade typically matches individual orders, including blocks, directly with each other (pay as bid). Profile trade requires to dissolve such a traditional 1-to-1 matching of intraday continuous trade and to instead match the individual products of a block against several counterparties, i.e., to introduce one-to-many, cross-matching, or even many-to-many matching.

In the following, we will distinguish between two "layers" to describe a possible new matching process: The trading layer is the visible layer for the market participants/traders and encompasses the actually traded power profiles. These profiles are possibly disaggregated, processed, and matched in the second layer, the processing layer, which represents the backbone of the actual technical matching process.

Once bids have been submitted on the trading layer by the different traders, on the processing layer the matching engine analyzes the pool of all submitted orders, both buy and sell orders, to verify whether and how a specific profile p_t fits into the pool and determines corresponding counterparties. If we denote the set of buyers by B and the set of sellers by S, we can formulate the problem of cross-matching as

$$\sum_{b \in B} p_{t,b}\, x_b = \sum_{s \in S} p_{t,s} x_s, \qquad \forall t,$$

where the binary variables $x_s \in \{0, 1\}$ and $x_b \in \{0, 1\}$ decide whether the respective seller or buyer is matched. Considering the intraday market as a pool and not as a P2P network is a novel aspect. Schumacher et al. (2019) have already highlighted that bilateral transactions may generally suffer from an efficiency loss compared to pool transactions. Against this finding, a shift towards cross-matching may also contribute to increased market efficiency on current intraday continuous markets.

In Fig. 5, we give a first example of cross-matching, where power consumption and power supply profiles are given for one producer and four consumers. For the sake of simplicity, we assume stepwise power profiles with 12 trading periods. Obviously, the five traders cannot be matched on a 1-to-1 basis. However, if the profiles of the four different consumers are aggregated into one demand power profile, this aggregated demand profile can be matched in each trading period with the single supply profile. Therefore, cross-matching on a 1-to-4 basis is possible and the single producer sells his power to four different consumers in the pool.

4.4. Further implications of power-profile trade, implementational issues, and policy conclusions

In addition to the described implications of power-profile trade on the matching on intraday continuous markets, there may be further implications of power-profile trade for an efficient market design and future electricity system. Even though a complete and in-depth description of all the necessary implementational steps is not possible within this perspective article, in the following, we highlight main questions that need to be answered in order to successfully implement power-profile trade.

- Necessary communication infrastructure and security: In order to be able to verify whether the contractually defined power profile was actually fed in or consumed, it will be essential to measure not only the average power amount in the contracted trading period, but also the actually realized power values within the trading period much more accurately. The corresponding communication infrastructure will therefore have significantly higher requirements with shorter latencies to process the increased amount of data. The introduction of smart meters is a first step to gather the necessary information from decentral consumers. Nevertheless, the question of adequate data processing capabilities remains – at least to some extent – an open issue. Furthermore, there will be important questions regarding the needed requirements for data protection and security that have to be answered by policymakers.
- Contractual definition of power profiles: Closely linked to the above issue, another major challenge encompasses the exact definition of the contractual obligations of the involved parties exchanging a power profile. Instead of defining a certain average amount of power that has to be physically delivered in a certain time frame, power-profile trade also involves aspects like a high-frequent measuring of different power amounts as highlighted above as well as defining tolerance bandwidths.
- Introduction/use of conditional orders: To ensure a reliable matching of power profiles at any point in time, the use of conditional orders could be pivotal to fill certain "gaps" that may arise in the matching. Conditional orders do not stipulate a fixed point in time for their execution, but instead base their execution on conditions like certain minimum or maximum prices. Such orders may also be suitable to increase the market participation of flexibility options like batteries or demand-side management in general. A higher certainty of achievable revenues via conditional orders based on, e.g., minimum prices, might then also lead to more security of investments for flexible assets on the spot market.
- Pricing: New pricing mechanisms may have to be developed, especially on intraday markets, in order to successfully implement the

trade of power profiles. The main challenge herein will lie in finding a market value for an individual profile that is jointly matched with others. As currently market participants that first place their order (initiator) set the price that must then be accepted by a counterparty (aggressor) on intraday continuous markets (using 1-1 matching), new pricing approaches may for instance rely on such a "first come, first set" principle. Nevertheless, the question of appropriate revenue sharing among the involved parties that are matched and the associated new complexity of future matching algorithms will be subject to further research (see also below).

- Optimization algorithms and heuristics: Related to the previous question, it will be necessary to develop suitable optimization algorithms. Considering continuous power profiles, it may be necessary to use heuristics instead of trying to find globally optimal solutions. In addition, power profiles of the trading layer may need to be disaggregated on the processing layer and then be solved using, e.g., new decomposition methods or cutting planes. The "suitable" size of disaggregated profiles will generally be a tradeoff between accuracy and processing speed, respectively complexity.

In addition to these specific questions, more general questions may arise, which for instance concern the future of balancing power markets and ancillary services: By trading power profiles, it will be possible to better account for short term fluctuations in the power system. Therefore, it may be possible to significantly reduce the amount of needed ancillary services. By this, also the role of the balancing responsible party (BRP) may change, which in turn will have implications for existing regulations.

Finally, we note that power-profile trade may neither be exclusively restricted to exchange trading nor to a specific country. In particular, the implementation of national power-profile trade should always be designed to fit into future rules regarding cross-border trade. In this context, corresponding cross-border cooperation of different countries is highly relevant, as we will only be able to successfully combat climate change together through an appropriate cross-border electricity system development that fosters flexibility (and in this way reduces curtailment of renewables). The former will be an important task for European policy making and for the corresponding European harmonization process.

5. Conclusions and policy implication

The expansion of renewable energy sources plays a major role in combating and reducing the effects of climate change. However, as a main characteristic, renewables are inherently intermittent and exposed to uncertainty stemming from unknown weather conditions. To exploit existing flexibility potentials of, e.g., consumers, storage facilities, or conventional backup generators, liberalized markets use price signals to disclose the relevant private information on the flexibility characteristics of assets. As such information is a priori not available to system operators, markets may yield a more efficient dispatch as compared to a traditional integrated system operator that centrally dispatched all assets of the power system.

However, with the use of fluctuating renewable energies and a necessary increase in the number of flexibility suppliers, current trading products must be developed in order to meet the new system requirements. Against this background, this paper outlines various adjustments of existing power-trading products of power exchanges contributing to an economically efficient and stable future power system. In this paper, we base our analysis on the European market design. Given this market framework, adjustments of different product parameters that define current power-trading products are considered, which include (1) local pricing, (2) temporal granularity, (3) minimum volumes, and (4) gate-closure times.

In addition to such a product evolution, given recent advances in data collection and data processing technologies, we argue that a shift towards power-profile trade may better capture the different flexibility characteristics of the available assets. In particular, since market participants know best their available flexibilities, it seems only natural that market participants themselves define the actual trading product. Such individually defined power profiles may not be matched against only one counterparty as it is currently standard on the intraday continuous market, but profiles may be matched against many counterparties. Thus, also on intraday continuous markets, corresponding cross-matching may be carried out in a pool of orders. To be able to implement profile trade, it will be necessary to measure the actual quantity of power with a finer temporal granular resolution within the imbalance settlement period, for example by using smart meters to collect the required data.

As future electricity systems will be characterized by many decentral, small players that have limited trading know-how, their active trading on electricity exchanges will require power-trading products with reduced complexity. From a small market participant's point of view, the proposed power-profile trade may offer such a reduced complexity and therefore positively affect their active market participation as highlighted in Section 4.2.

Ultimately, using power-profile trade, the integration of power as part of the product definition with a more precise replication of production or consumption ramps could enable new (small) power generators and consumers to trade products that better match their asset characteristics. As a result, also fewer public grid interventions may be necessary, and the need for balancing power may decrease. For transmission and distribution system operators, in particular, the prevention of critical grid situations at hourly changes could be decisive.

The proposed new perspective on power-trading products opens up a number of questions that must be addressed in future as highlighted in the last section. In this context, it is particularly important to identify those parties who will be responsible for the implementation of the different evolutionary approaches as well as for the required steps towards power-profile trade. Obviously, different technical, economic, and legal issues have to be clarified in this respect. Being able to better align power trade to the requirements of a future RES-based power system under an energy-only paradigm through a development of power-trading products, we may finally contribute to the achievement of the goals of the Paris Agreement.

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.

References

Alizadeh, M I, Parsa Moghaddam, M, Amjady, N, Siano, P, Sheikh-El-Eslami, M K, 2016. Flexibility in future power systems with high renewable penetration: a review. Renew. Sustain. Energy Rev. 57, 1186–1193. doi:10.1016/j.rser.2015.12.200 .

Arentsen, M J, Künneke, R W, 1996. Economic organization and liberalization of the electricity industry. Energy Pol. 24 (6), 541–552. doi:10.1016/0301-4215(96)00044-4 .

Barth, R, Weber, C, Swider, D J, 2008. Distribution of costs induced by the integration of RES-E power. Energy Pol. 36 (8), 3107–3115. doi:10.1016/j.enpol.2008.03.039 .

J. Bertsch Is an inefficient transmission market better than none at all? On zonal and nodal pricing in electricity systems. EWI Working Paper 15/05. Köln: Institute of Energy Economics at the University of Cologne (EWI)https://www.econstor.eu/bitstream/10419/121257/1/834473844.pdf2015

Bjørndal, M, Jørnsten, K, 2001. Zonal pricing in a deregulated electricity market. Energy J. 22 (1), 51–73.

Bjørndal, M, Jørnsten, K, Pignon, V, 2003. Congestion management in the nordic power market — counter purchases and zonal pricing. Compet. Regul. Netw. Ind. 4 (3), 271–292. doi:10.1177/178359170300400302 .

Bohn, R E, Caramanis, M C, Schweppe, F C, 1984. Optimal pricing in electrical networks over space and time. Rand J. Econ. 15 (3), 360–376. doi:10.2307/2555444 .

Bower, J, Bunn, D W, Wattendrup, C, 2001. A model-based analysis of strategic consolidation in the German electricity industry. Energy Pol. 29 (12), 987–1005. doi:10.1016/S0301-4215(01)00034-9 .
Burke, M J, Stephens, J C, 2017. Energy democracy: goals and policy instruments for sociotechnical transitions. Energy Res. Soc. Sci. 33, 35–48. doi:10.1016/j.erss.2017.09.024 .
5/10/2012 - 5/12/2012 Burstedde, B, 2012. From nodal to zonal pricing: a bottom-up approach to the second-best. In: 2012 9th International Conference on the European Energy Market. 2012 9th International Conference on the European Energy Market (EEM 2012). IEEE, Florence, Italy, pp. 1–8 [Place of publication not identified].
Chao, H-P, Peck, S, 1996. A market mechanism for electric power transmission. J. Regul. Econ. 10 (1), 25–59. doi:10.1007/BF00133357 .
Cramton, P, 2017. Electricity market design. Oxf. Rev. Econ. Pol. 33 (4), 589–612. doi:10.1093/oxrep/grx041 .
Doege, J, Schiltknecht, P, Lüthi, H-J, 2006. Risk management of power portfolios and valuation of flexibility. Spectrum 28 (2), 267–287. doi:10.1007/s00291-005-0005-4 .
Doostizadeh, M, Ghasemi, H, 2012. A day-ahead electricity pricing model based on smart metering and demand-side management. Energy 46 (1), 221–230. doi:10.1016/j.energy.2012.08.029 .
EPEX SPOT SE, 2019. EPEX Spot Operational Rules. p. 72.
EPEX SPOT SE Tradinghttps://www.epexspot.com/en/product-info2019accessed 19 June 2019
European Union, 2019. Clean Energy for All Europeans. p. 24.
Golombek, R, Brekke, K A, Kittelsen, S A C, 2013. Is electricity more important than natural gas? Partial liberalizations of the Western European energy markets. Econ. Modell. 35, 99–111. doi:10.1016/j.econmod.2013.06.023 .
Goutte, S, Vassilopoulos, P, 2019. The value of flexibility in power markets. Energy Pol. 125, 347–357. doi:10.1016/j.enpol.2018.10.024 .
Graf, C, Wozabal, D, 2013. Measuring competitiveness of the EPEX spot market for electricity. Energy Pol. 62, 948–958. doi:10.1016/j.enpol.2013.07.052 .
Grimm, V, Martin, A, Schmidt, M, Weibelzahl, M, Zöttl, G, 2016. Transmission and generation investment in electricity markets: the effects of market splitting and network fee regimes. Eur. J. Oper. Res. 254 (2), 493–509. doi:10.1016/j.ejor.2016.03.044 .
Grimm, V, Martin, A, Weibelzahl, M, Zöttl, G, 2016. On the long run effects of market splitting: why more price zones might decrease welfare. Energy Pol. 94, 453–467. doi:10.1016/j.enpol.2015.11.010 .
Hagemann, S, Weber, C, 2013. An Empirical Analysis of Liquidity and its Determinants in the German Intraday Market for Electricity. EWL Working Paper (17/13).
Henriot, A, Glachant, J-M, 2013. Melting-pots and salad bowls: the current debate on electricity market design for integration of intermittent. RES Util. Pol. 27, 57–64. doi:10.1016/j.jup.2013.09.001 .
Hiroux, C, Saguan, M, 2010. Large-scale wind power in European electricity markets: time for revisiting support schemes and market designs? Energy Pol. 38 (7), 3135–3145. doi:10.1016/j.enpol.2009.07.030 .
Hogan, W W, 1992. Contract networks for electric power transmission. J. Regul. Econ. 4 (3), 211–242. doi:10.1007/BF00133621 .
Holttinen, H, 2005. Optimal electricity market for wind power. Energy Pol. 33 (16), 2052–2063. doi:10.1016/j.enpol.2004.04.001 .
Klessmann, C, Nabe, C, Burges, K, 2008. Pros and cons of exposing renewables to electricity market risks—a comparison of the market integration approaches in Germany, Spain, and the UK. Energy Pol. 36 (10), 3646–3661. doi:10.1016/j.enpol.2008.06.022 .
Koch, C, Hirth, L, 2019. Short-term electricity trading for system balancing: an empirical analysis of the role of intraday trading in balancing Germany's electricity system. Renew. Sustain. Energy Rev. 113, 109275. doi:10.1016/j.rser.2019.109275 .
Kubli, M, Loock, M, Wüstenhagen, R, 2018. The flexible prosumer: measuring the willingness to co-create distributed flexibility. Energy Pol. 114, 540–548. doi:10.1016/j.enpol.2017.12.044 .
Kumar David, A, Wen, F, 2001. Market power in electricity supply. IEEE Trans. Energy Convers. 16 (4), 352–360. doi:10.1109/60.969475 .
Märkle-Huß, J, Feuerriegel, S, Neumann, D, 2018. Contract durations in the electricity market: causal impact of 15 min trading on the EPEX SPOT market. Energy Econ. 69, 367–378. doi:10.1016/j.eneco.2017.11.019 .
Oggioni, G, Smeers, Y, 2013. Market failures of Market Coupling and counter-trading in Europe: an illustrative model based discussion. Energy Econ. 35, 74–87. doi:10.1016/j.eneco.2011.11.018 .
Pechan, A, 2017. Where do all the windmills go? Influence of the institutional setting on the spatial distribution of renewable energy installation. Energy Econ. 65, 75–86. doi:10.1016/j.eneco.2017.04.034 .
Remppis, S, Gutekunst, F, Weissbach, T, Maurer, M, 2015. Influence of 15-minute Contracts on Frequency Deviations and on the Demand for Balancing Energy: Die Energiewende - Blueprints for the New Energy Age. VDE Verlag, Berlin, 1 CD-ROM.
Réseau de transport d'électricité Network frequencyhttps://clients.rte-france.com/lang/an/visiteurs/vie/vie_frequence.jsp2019accessed 12 July 2019
Rieß, S, Neumann, C, Glismann, S, Schoepf, M, Fridgen, G, 2017. Rethinking short-term electricity market design: options for market segment integration. In: 2017 14th International Conference on the European Energy Market (EEM): 6-9 June 2017, Dresden, Germany. 2017 14th International Conference on the European Energy Market (EEM), Dresden. IEEE, Piscataway, NJ, pp. 1–6 6/6/2017 - 6/9/2017.
Schumacher, L, Küpper, G, Henneaux, P, Bruce, J, Klasman, B, Ehrenmann, A, 2019. The Future Electricity Intraday Market Design. Publications Office of the European Union, Luxembourg 1 online resource.
Schweppe, F C, Caramanis, M C, Tabors, R D, Bohn, R E, 1988. Spot Pricing of Electricity. Springer, Boston, MA, p. 384.
Ulbig, A, Andersson, G, 2015. Analyzing operational flexibility of electric power systems. Int. J. Electr. Power Energy Syst. 72, 155–164. doi:10.1016/j.ijepes.2015.02.028 .
Viehmann, J, 2017. State of the German short-term power market. Z. Energiewirtschaft 41 (2), 87–103. doi:10.1007/s12398-017-0196-9 .
Weibelzahl, M, 2017. Nodal, zonal, or uniform electricity pricing: how to deal with network congestion. Front. Energy 11 (2), 210–232. doi:10.1007/s11708-017-0460-z .
Weissbach, T, Welfonder, E, 2009. High frequency deviations within the European Power System: origins and proposals for improvement. In: IEEE/PES Power Systems Conference and Exposition. 2009 IEEE/PES Power Systems Conference and Exposition (PSCE). IEEE, Piscataway, NJ, pp. 1–6 Seattle, WA, USA. 3/15/2009 - 3/18/2009.
Wilson, R, 2002. Architecture of power markets. Econometrica 70 (4), 1299–1340. doi:10.1111/1468-0262.00334 .