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Philipsen, Rens; Morales-Espana, G.; de Weerdt, Mathijs; de Vries, Laurens

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A NEW MARKET DESIGN FOR DAY-AHEAD MARKETS WITH POWER-BASED SCHEDULING

Rens Philipsen, Germán Morales-España, Mathijs de Weerdt and Laurens de Vries

Introduction

With the introduction of renewable energy sources (RES) to the electricity system, the European electricity market must undertake a number of changes if its current security of supply is to be maintained. In electricity systems, supply and demand must be in balance at all times. In order to accommodate for the increased installation of RES capacity, we must compensate for fluctuations in both supply and demand. To ensure this balance, we employ markets to coordinate who consumes or supplies how much energy during a programme time unit (PTU). Any remaining imbalance during a PTU is covered by reserves, which are contracted by the system operator.

Existing electricity markets, however, inefficiently use the available reserves, because the penalizing mechanism for imbalances is based on the total energy supplied or consumed during a PTU. Even with such a mechanism in place there is no guarantee that momentary imbalances do not arise. While the total amounts of energy supplied and consumed during the entire PTU are equal, it would be incorrect to assume this balance also holds at each moment.

What is perhaps even more staggering is that this system in fact *is responsible for* momentary imbalances: while aggregated electricity demand is mostly a smooth curve, power plant operators sharply change their output at the start of a PTU in order to supply the contracted energy. This behaviour causes deterministic and predictable shocks in system frequency which can be observed all over Europe [1]. Despite recent advancements, our existing electricity markets are therefore far from optimal: even if no uncertainty exists, they are unable to prevent imbalances.

It is important to note the effect this has on RES integration and the reduction of thermal power plants: as more intermittent resources are connected, the share of thermal power plants can only decrease if they are not needed for the provision of reserves. The share of RES in the generation mix is therefore capped by the necessity of maintaining reserves, and that cap is artificially lowered by our overly high reserve requirements caused by imperfections in the market design. As reserves are usually procured for a longer period of time, thermal generators are effectively subsidised, making RES relatively less competitive. Consequently, these deterministic imbalances, stemming from the market design, hold back the widespread adoption of RES in Europe.

Our proposed solution is to make day-ahead schedules based on *momentary power output*, rather than total energy output. This would be a radical change in the way the electricity system is operated from day to day, freeing up flexible resources to deal with actual uncertainty, rather than with deterministic scheduling inaccuracies. Such power-based scheduling was proposed and analysed in [2] and [3]. In power-based scheduling, day-ahead schedules assigned to both generators and loads are defined as piecewise linear trajectories. These power trajectories ensure that day-ahead schedules are actually in continuous balance, and can better account for the actual physical constraints on the system. Traditional energy-based scheduling, by contrast, does not correctly incorporate generator flexibility. This flexibility can be both over- and under-estimated in making schedules, resulting in infeasible solutions in the first case, and inefficient solutions in the second. As a consequence of that, power-based scheduling is a necessary step towards a more efficient operation of the electricity system.

The challenge we currently face is to implement this technological solution in practice. Although the technical advantages are well-understood [2], [4]–[7], it is as of yet unclear which changes in the market regime must be effected in order to make power-based scheduling the standard. Products must be redefined, and, as a result, changes may be necessary on the way markets are cleared and products priced. We therefore start by describing the minimal requirements to which a newly designed market should conform. From there, we propose a combination of market rules which ensure a continuous network balance, enabling more efficient use of the available generation capacity.

The central question we aim to answer is the following: *which set of market rules can efficiently ensure that there exists a moment-to-moment balance of supply and demand in day-ahead planning?*[1]

Market design

To delineate our analysis, we focus on a specific market, close to the existing market design: day-ahead is cleared 24-36 hours ahead, in a single discrete two-sided auction. For this discrete auction, we must define the following aspects: bid definition, clearing rules, and pricing rules. We specify these in the following sections. Broadly speaking, we define multi-period bids as our starting point, where parties communicate their physical constraints (such as ramping or output limits), soft constraints (such as deadlines) and variable costs. The market is cleared for a fixed horizon (e.g., the next day) and communicates the precise power trajectories all parties will have to follow. We then discuss the minimal requirements a pricing mechanism should conform to, and define prices as a price per megawatt (and not megawatt-per-hour) of output at the end of each PTU.

Bid definition and clearing rule

The first step is to define what constitutes a bid. In defining a bid, we opt for a broader bid than the existing hourly orders in order to better capture the true flexibility offered by both sides of the market. Our preferred option is for both power plants and consumers to place bids which closely resemble their physical characteristics. Bids consist of lower and upper production limits, maximum up and down ramp rates, and a price for energy. Furthermore, these bids can be extended by including minimal and maximal total energy demand.

We emphasize two things: first of all, this bid definition is a generalization of the bids possible in the existing markets, and can therefore recreate them without any loss of accuracy. On the other hand, they can be extended in the same manner to include more complex constraints, such as minimal income conditions, block orders, or linked orders. Such bids can then be used to incorporate physical or economical restrictions, but their use is likely to be lower than in current markets due to the fact that our basic bid already allows for restrictions on the range within which a plant can be operated.

Pricing rule

Primarily, our aim is to guarantee *cost recovery* for both generators and loads: no generator will produce electricity below its cost, and no consumer will pay more than its willingness to pay. In terms of mechanism design, this means we insist on *ex-post individual rationality*.[2] As a second objective, we aim for *socially efficient outcomes*.[3] This is a very natural objective for a regulating authority and is already the objective of the existing Euphemia [9] algorithm. Thirdly, the market operator should stick to that function only, and should not have to contribute any money to transactions. We therefore ask for a *strictly balanced budget* as a third requirement.[4]

Economic theory, unfortunately, contains a number of impossibility theorems which show it is impossible to design a market which is provably impervious to manipulation, given the objectives described above. Note that this does not imply it will be easy to influence a market, nor does it say anything about how inefficient the market will be if bidders behave strategically. Although robustness against manipulation is important, we leave the issue of *how* vulnerable a

1 Although we focus here on day-ahead markets, the proposed market design can (and should) be applied to any other market, e.g., intraday or real-time markets.

2 Participants to the mechanism receive non-negative utility from participating in all possible states of the market (ex-post).

3 Given the bids of all generators and load-serving entities, social welfare is maximized.

4 A mechanism is budget-balanced if the sum of payments by the market operator is precisely zero.

market design is to manipulation for future work, and for now note only that we cannot give a theoretical guarantee.

Marginal cost pricing is already well-established in the power systems community. It follows from the dual variables which are associated with constraints in mathematical optimisation problems. These dual variables, in an economic setting also referred to as shadow prices, indicate the sensitivity of the objective function to a relaxation of that constraint. These shadow prices form a competitive equilibrium and ensure envy-free prices for all participants, who all recover their costs [8]. This in turn implies individual rationality. They are therefore suitable candidates for our pricing rule.

In defining shadow prices, we must overcome one hurdle. In our redesigned market, PTUs are irrevocably linked to each other due to the linear power trajectories, where increasing the output of a generator at the end of one PTU increases the amount of energy in both the preceding and in the subsequent PTU. Although these trajectories correspond to a unique energy profile, we do not price the energy profiles themselves: instead, we define point-to-point schedules, and we therefore base prices on the power output at these points, which lie at the end of a PTU. Using the shadow price of the power balance constraint at the end of an hour as the price for power delivery at that moment, bidders are rewarded for being able to provide both energy as well as ramping flexibility – analogous to the value for providing energy *in the right location* when locational marginal pricing is applied. The total payment to a generator then equals its output at the end of an hour times that price.

Difference with existing markets

Now that the necessary rules for a market implementing power-based scheduling have been outlined, we compare the resulting market with the existing day-ahead market. One of the advantages of a power-based approach is that flexible demand can be rewarded for its flexibility in the day-ahead market already. Since the payments to the market participants now consist of both an energy part and a ramping part, it is easier to properly schedule the flexibility offered by flexible parties. This is especially important for flexible load, as they may have a maximum consumption constraint.

Our work in [7] compares alternative formulations of the day-ahead optimal scheduling problems, based on unit commitment (UC) formulations. Case studies are carried out on the IEEE 118-bus test system. When comparing ideal stochastic energy-based with power-based UCs, the power-based UC presented 33% less curtailment and 5% lower actual operational costs.

Conclusions

Existing electricity markets are inefficient. Ensuring energy balance during a PTU, unfortunately, does not guarantee the momentary balance of supply and demand which is a necessary condition for the safe and reliable operation of electrical power systems. Power-based scheduling can alleviate the imbalances which follow from the existing market design, preventing frequency shocks which threaten security of supply and freeing up expensive reserves. This reduces costs for consumers and reduces the need for online thermal power plants, improving the competitive position of renewable electricity sources. Day-ahead schedules based on power trajectories are, in all ways, superior to energy-based schedules.

Coordinating power-based trajectories in a market was until now an unresolved problem. Our market proposal fills this gap by providing bid definitions and rules for bidding, market clearing, and pricing, delivering a comprehensive overview of the changes necessary to arrive to a power-based future. The proposed market model is very much in line with the operation of existing markets, making only the minimal changes necessary to fully capture the advantages of power-based scheduling. In doing so, it improves economic efficiency and makes way for further integration of RES.

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