Two-stage unit commitment modeling for virtual power plants

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The development of an increasingly decentralized, renewable power supply requires adequate planning approaches. Compared to unit commitment planning in regulated markets with a dominant share of dispatchable power generation, power systems with large shares of intermittent renewable power sources such as wind or photovoltaics are subject to uncertain supply as well as uncertain load forecasts and prices.

Virtual Power Plants have been developed to aggregate intermittent renewables with so-called flexibility options, which include dispatchable power plants, storage systems and flexible power consumers. Dispatchable power plants, such as biogas plants, include all that can actively be committed to supply power in a time interval. Storage systems, such as pumped-storage hydroelectricity, can store power in times of low prices and resell it when prices rise. Flexible power consumers, such as operators of electric vehicles, can attempt to use these time windows to load the batteries, lowering their power purchasing costs.

In the current German power market, power can be traded either in auctions on the day before physical delivery or in continuous intraday trading on the day itself. To determine optimal schedules for flexibility options in the context of day-ahead or intraday markets, a two-stage unit commitment model is presented to deal with the uncertainty of market prices resulting from the interplay of power generation in wind turbines and photovoltaic cells one the one hand with power demand on the other.

1.1 Introduction

The continuous expansion of renewable power generation in Germany leads to a variety of new planning problems. The power output of the two largest groups of renewable energy plants, photovoltaics and wind power, is intermittent, which means that other components of the energy system need to be adapted to react to these fluctuations. As power can only be stored to a very limited extent, such adaptations usually include adapting dispatchable power suppliers, customers with flexible demands and available storage options. Dispatchable power plants, flexible customers and storage devices are referred to as “Flexibility Options” (FO) in this context. In the course of the expansion of volatile power generation capacity, an increasing number of concepts and technologies are being considered as FO. As the cost of supplying flexibility differs considerably between these technologies, a methodology is required to assess the economic viability of combining intermittent power plants and FO.

1.2 Trading power generation flexibility in Germany

A single aggregator, such as a Virtual Power Plant (VPP), often controls numerous Flexibility Options. VPPs aggregate several intermittent power sources and FO to make power generation more predictable and thus reliable. As part of a VPP, intermittent power sources can pass the prequalification that is required for participating in market auctions as well as avoid punishing costs for balancing power in case of faulty production forecasts. In addition to enabling the market participation of intermittent power sources, the aim of a VPP is to apply the available flexibilities to different markets to maximize profit of their operation (Helms et al., 2016). In the following two sub-sections, both different kinds of flexibility options and the potential markets are introduced.

The flexibility that is required to balance supply and demand of power can be found in several parts of the power system. While some flexibility also exists in the management of the power grid itself, the most significant FOs are flexible power suppliers, flexible consumers and a diversity of storage systems.

Since the liberalization of the German power sector, several marketplaces have been established to facilitate power trading. Among the most significant marketplaces in this context are the day-ahead auction, intraday auction and the continuous intraday trading of the European Power Exchange (EPEX) and the various forms of ancillary service markets.

To take part in the day-ahead or intraday auctions, bids on an hourly basis must be submitted on the day before physical delivery. Soon after, the market clearing price is announced for each of the 24 hours of the following day (EPEX 2018). Due to the similarity between the two, the intraday auction will not be discussed in further detail in this paper.

In contrast to the two auctions described before, trading can take place until 30 minutes before physical delivery. Additionally, there is no market clearing price, but 15-minute contracts are traded whenever there is a match between supply and demand of power for a specific time window. During intraday trading, it is uncertain whether reasonably priced power offers will be (or become) available in time before the moment of physical delivery. Therefore, contrary to auctions, the continuous trading requires making numerous decisions throughout the day, as bids may become available any time until 30 minutes before delivery. To our knowledge, no model currently takes the additional possibility to trade in the continuous intraday trading into account.

If individual actors on the power market fail to cover their power requirements in either one of the auctions or through the continuous intraday trading, they need to purchase balancing power from the transmission system operators (TSOs), often at unfavorable prices.

1.3 Modeling flexibility options with optimization models

When modeling the optimal use of flexibility on the described power markets, two stage models can be used to represent initial dispatch and redispatch for example on the second day (Huang, 2017). Contrary to existing models, the following optimization model models a potential market interaction on two markets, both the day-ahead auction and the continuous intraday trading (Hospes, 2018). In an exemplary combined model for a flexible biogas plant and pumped-storage hydroelectricity as supply-side FOs and a PV plant as an intermittent renewable power producer, it is possible to explore the value of a combined marketing of dispatchable and intermittent power sources.

In the first stage, i.e. as preparation for the day-ahead auction, the output of the PV plant is calculated based on a forecast of solar radiation of the next day (Konstantin, 2013).

$$\varphi_i^{DA} A \eta \omega = P_i^{PV,DA} \tag{1}$$

Where:

φ_i^{DA}	*day-ahead forecast for the solar radiation in hour i (kW/m²)*
A	*area of the PV plant (m²)*
η	*efficiency of converting solar radiation into power (%)*
ω	*performance ratio of real vs. ideal yield of a PV plant (%)*
$P_i^{PV,DA}$	*forecasted power from the PV plant in hour i (kW)*

The biogas plant's and pumped-storage hydroelectricity's operating hours are chosen with the following two optimization models based on a forecast of the day-ahead prices. For the biogas plant, revenues based on the day-ahead (DA) prices are maximized under the constraints that the biogas, of which there is a constant production PBGP,G that is independent of power generation PBGP,P, can be stored, and that the power generator operates within feasible limits.

$$max \sum_{i=1}^{I} \left(p_i^{DA} P^{BGP,P} x_i \right) \tag{2}$$

$$cap_j^{BGP} = cap_0^{BGP} + P^{BGP,G} \cdot j - P^{BGP,P} \sum_{i=0}^{j} x_i \tag{3}$$

$$cap_{min}^{BGP} \leq \ cap_j^{BGP} \leq cap_{max}^{BGP} \tag{4}$$

$$0.35 \leq \ x_i \leq 1 \tag{5}$$

cap_j^{BGP}	*state of biogas storage capacity in time slot j*
p_i^{DA}	*day-ahead power price in time slot i*
$P^{BGP,G}$	*capacity of the biogas production*
$P^{BGP,P}$	*capacity of power generation*

For the pumped-storage hydroelectricity model, a term for the value of stored electricity is added. This term is meant to avoid that the energy stored at the beginning of the planning horizon is depleted even when power prices are low. In contrast to the biogas model, the value of stored energy only grows if pumps fill the reservoir with water (i.e. $y_i < 0$).

$$max\sum_{i=1}^{I}\left(\left(p_i^{DA}-p_{I+}\right)P^{PSH}y_i\right) \quad (6)$$

$$cap_j^{PSH}=cap_0^{PSH}-P^{PSH}\cdot\sum_{i=0}^{j}y_i \quad (7)$$

$$cap_{min}^{PSH}\leq\ cap_j^{PSH}\leq cap_{max}^{PSH} \quad (8)$$

$$-1\leq\ y_i\leq 1 \quad (9)$$

cap_j^{PSH} *state of pumped-storage capacity in time slot j*

P^{PSH} *capacity of the pumped-storage hydroelectricity*

1.4 Application, results and discussion

This combined optimization model (equations 2, 6 and 12) is applied on an exemplary day on which the solar radiation is assumed to be greater than anticipated before the day-ahead auction. As deviations between forecasts and actual prices are hardly available, we show the functionality of the algorithm with a hypothetical case study day. The VPP's assumed characteristics are shown in Table 1.

Table 1. Parameter values for the exemplary VPP.

Parameter	Value	Parameter	Value
A	36,176 m²	cap_{min}^{BGP}	0 (MWh_{el} equiv.)
η	13.8%	cap_{max}^{BGP}	4 (MWh_{el} equiv.)
ω	80%	P^{PSH}	1 MW
$P^{BGP,G}$	1 MW	cap_{min}^{PSH}	0 (MWh_{el} equiv.)
$P^{BGP,P}$	0.5 MW	cap_{max}^{PSH}	8 (MWh_{el} equiv.)
		p_{I+}	35 €/MWh

On this hypothetical day, we assume that both the PV production of the VPP would be greater than the bids on the day-ahead market and that power prices around noon in the continuous intraday trading turned negative (to -99 €/MWh, see Figure 1). At such prices, it would be very disadvantageous to sell power on the market.

If it is assumed that this surplus must be sold in the continuous intraday trading, the PV plant alone would face negative revenues of -71,3 € on that day. Adding a biogas or pumped-storage hydroelectricity plant results in positive revenues of 614,64 € and 596,89 €, respectively. A VPP consisting of all three plants results in revenues of 1282,83 € and significantly reduces the power produced in the critical hours around noon/ midday compared to the day-ahead auction. However, if sufficient power volumes can still be traded on the intraday market, these values exactly equal the sum of the revenues of the PV plant and the other two plants if they participated in both day-ahead auction and intraday trading individually. While a redispatch clearly makes sense under these circumstances, the common marketing within a Virtual Power Plant only adds utility to all participants if an internal reaction helps avoid e.g. high prices for balancing power.

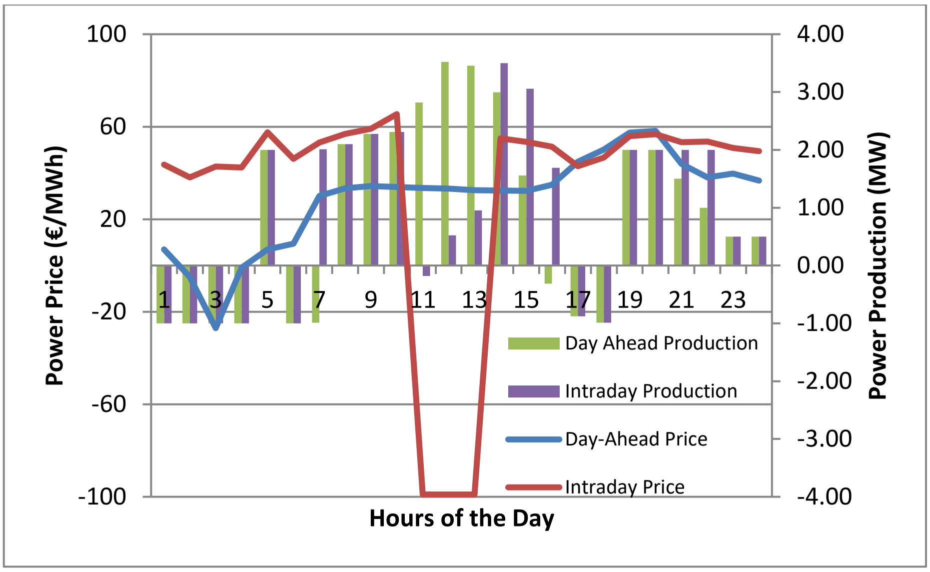

Figure 1: Unit commitment of the VPP on day-ahead and intraday markets.

If the response is measured against a liquid intraday market (in which all kinds of FO can participate), the developed methodology shows that VPPs represent a zero-sum game given that all aggregated FOs can buy and sell unlimited quantities of power in that market. The benefit of aggregating dispatchable and intermittent power plants becomes more decisive when such trading quantities are not available in an hour j, or several hours. In the developed model, this can be included by adding a term to the objective function that subtracts the value of R_j multiplied by the cost of balancing power in hour j from the revenues earned in day-ahead auction and intraday trading. If the cost of balancing power is greater than the shadow price of restricting R_j, the optimal intraday schedule of the VPP changes accordingly.

1.5 Conclusion and outlook

The presented methodology can be applied to react to deviations between forecasted and real production values, as well as between day-ahead and intraday prices. It becomes apparent that combining intermittent and dispatchable power plants into an aggregated virtual power plant does not result in immediate gains in trading revenues if sufficiently liquid markets are assumed. The benefit of aggregation for PV plant owners lies in the more reliable power output (i.e. lower cost for balancing power) and in passing the pre-qualification that is required for participation for power trading. For owners of dispatchable power plants, the benefit of participating in VPPs is in the service of marketing their plants on markets, which is increasingly necessary to receive sufficient income for an economic operation.

Further research could include stochastic or robust optimization approaches to deal with deviations between forecasted and real power production from intermittent sources and the effects of such deviations on intraday prices.

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