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On the effects of storage facilities on optimal zonal pricing in electricity markets

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ABSTRACT

This paper analyzes the effects of storage facilities on optimal zonal pricing in competitive electricity markets. In particular, we analyze a zonal pricing model that comprises consumers, producers, and storage facilities on a network with constrained transmission capacities. In its two limit cases, our zonal pricing model includes the reference nodal pricing model as well as the uniform pricing model with storage. To the best of our knowledge we are the first to analyze zonal pricing in the presence of storage. As our numerical results show, storage facilities do not only reduce the inter-temporal price volatility of a market, but may considerably change the inter-regional price structure. In particular, the inter-regional price volatility may increase in the presence of storage, which may imply a complete reconfiguration of optimal zonal boundaries as compared to the no-storage case. However, market participants may have an incentive to keep or implement a sub-optimal zonal design. Thus, storage facilities will in general challenge optimal congestion management with common heuristic approaches to configure optimal price zones (e.g., the use of congested transmission lines of a nodal pricing system) not always suggesting optimal zonal configurations. Therefore, we propose a model extension that allows policy makers to determine welfare maximizing zonal configurations, which account for the complex inter-regional price effects of storage facilities. Especially with regard to increasing storage investments, such a model may help to (at least partially) handle the described inefficiency problems regarding sub-optimal zonal designs that may challenge European or Australian zonal electricity markets in the near future.

1. Introduction

Recently, storage facilities and their effects on electricity prices are gaining increasing interest in the field of energy market policy. As a main characteristic, storage facilities allow to store electricity in a given (low demand) period in order to being able to use the corresponding discharged electricity in one of the subsequent periods in a welfare-enhancing way; see for instance Walawalkar et al. (2007). In this context, storage may be used as a backup to meet time-varying demand or generation; amongst others, see Su et al. (2001), Bathurst and Strbac (2003), or DeCarolis and Keith (2006). In addition, storage facilities will in general reduce high peak-period prices, which yields a less volatile inter-temporal price development. Such a smoothened price structure is frequently highlighted by different authors including Sioshansi et al. (2009), Sioshansi (2010), Gast et al. (2013), or Sioshansi (2014).[1] However, these studies mainly abstract from transmission constraints and do not account for the chosen network management system. To the best of our knowledge we are the first to analyze the effects of storage facilities on electricity prices under different congestion management methods including zonal pricing and nodal pricing. In particular, this paper shows that storage may not only yield a smoother inter-temporal price development with reduced price fluctuations, but may totally change the inter-regional price structure of an electricity network. To be more precise, the inclusion of storage facilities on a network may increase inter-regional price differences as compared to a market without storage. Such an increase in the inter-regional price volatility may have considerable effects on optimal zonal pricing and on optimal price zone configurations. Interestingly, these results are obtained already for simple networks without loop flows.

Our work directly contributes to the vast literature on congestion management regimes. Even though nodal pricing is known to yield a first best outcome (see also Bohn et al., 1984, Hogan, 1992, or Chao and Peck, 1996), a system of zonal prices reduces the complexity as compared to a nodal pricing system, since fewer prices must be computed.

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[1] Besides this economic-related literature, a huge number of articles on technical and scheduling aspects of storage facilities exists, which are, however, not the focus of this paper; see for instance Manwell and McGowan (1993), Glavin et al., (2008), or Tuohy and O'Malley (2009).

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Therefore, given this complexity reduction, a zonal system is often seen as being politically and organizationally more favorable. However, as it is well known from the no-storage case, determining an optimal, welfare maximizing zonal design with adequate boundaries is in general a very challenging task; see for instance Walton and Tabors (1996), Stoft (1997), Hogan (1998), or more recently Grimm et al. (2016a). Bjørndal and Jørnsten (2001) were among the first to study zonal pricing in a network-based model with generation and demand that are linked by limited transmission lines. As a main result, zonal pricing may be accompanied by a welfare loss as compared to nodal pricing, with different zonal configurations affecting welfare and rents of different market participants. In addition, the authors show that already for a fixed number of price zones, the optimal zonal boundaries can only be determined as the solution to a mixed-integer optimization problem. Ehrenmann and Smeers (2005) further study zonal pricing in an equilibrium model, where the actual transmission lines between zones are replaced by aggregated inter-zonal transmission links. Such a model variant is commonly referred to as second-best zonal pricing. In an extension, Oggioni and Smeers (2013) study the welfare losses of a second-best bilevel zonal pricing model with subsequent redispatch. In Grimm et al. (2016a) and Grimm et al. (2016b) these models are further generalized to the case of endogenous generation investments in a long-run model. Note that none of these studies considers effects of storage facilities on optimal zonal pricing and on corresponding price zone configurations. Therefore, in this paper we show that also in very simple networks, information on the optimal zonal configuration of a model without storage may not indicate optimal zonal compositions of energy markets with storage. In addition, market participants may have an incentive to implement or keep a sub-optimal zonal decomposition in order to maximize their rents. This may cause severe acceptance and incentive problems in electricity markets. Note that for the no-storage case Bjørndal and Jørnsten (2001) have already shown that there may be conflicting interests between producers and consumers and that small changes in market parameters may change optimal zones. In this context, we provide a model extension that endogenously determines an optimal zonal configuration for electricity markets with storage.

As zonal pricing is currently applied in various European countries and in Australia, our work adds valuable policy-relevant insights in times of increasing storage facility investments. In summary, our work reaches the following policy implications of storage in electricity systems:

- Independent of the chosen congestion management regime, in competitive electricity markets the integration of storage facilities is in general beneficial and should therefore be promoted by policy makers. As one main reason, storage facilities allow for a more efficient balancing of demand and supply over time by selling or buying their electricity at the spot market in the different periods. Given comparatively fast reaction times of battery storages or pumped hydropower storages, market clearing that is currently made on an hourly or even on a daily basis may be organized in shorter trading intervals in order to realize the possible welfare gains of storages by a better inter-temporal demand-supply balancing. In this context, the National Electricity Market in Australia that consists of five different regions already determines the spot market price for each half-hourly interval; see Energy EXchange (2017).
- In times of the low-carbon transformation of the electricity system, storage facilities have an implication on the optimal zonal configuration by changing the inter-regional price structure. Therefore, storage has to be regarded in the discussion on a welfare-optimal reshaping of price zones. In general, a simple adoption of the zonal design under the no-storage case will not suffice to ensure an optimal zonal configuration if storage facilities are considered. In contrast, policy makers and regulators should reconsider their implemented zonal division of the grid including the number of price zones and their boundaries. Note that a welfare-maximizing zonal design will highly depend on the demand-generation pattern as well as on available transmission facilities of the network under consideration. Therefore, the optimal reshaping of the zonal design that comes along with the introduction of storage may not always be the same for all electricity networks, but must rather be decided on the basis of a detailed quantitative economic analysis that takes relevant technical and economic restrictions of the considered electricity network into account; see also our sensitivity analysis in Section 5. Such a process of discussing and analyzing the re-configuration of price and bidding zones is well under way in Europe and should be promoted. A current example is the discussion of a possible split of the German-Austrian price zone; see European Energy Exchange (2017). However, despite the growing importance of storages with increased capacities stemming from the low-carbon transformation of the energy system, the current process of European bidding-zone review did not yet raise the issue of storage facilities; compare ACER (2014), ENTSO-E (2014), or ENTSO-E (2015).
- The use and value of a storage facility highly depends on its location within the network as well as on current transmission limitations. Therefore, in the long-run policy makers face not only the problem of a welfare-maximizing zonal design that ensures an optimal integration of existing storages within the given electricity network (see also the discussion in the previous bullet point), but policy makers must also ensure a zonal design that incentivizes optimal investments with adequate capacities and locations. In this context, long-run decision making must always account for the interdependency between storage and transmission facility investments that highly depend on each other. Most interestingly, there will not always be a conflicting relationship between the network and storages, but there may be situations where public transmission and private storage investments mutually support each other.[2]

This paper is organized as follows. We first introduce our model framework in Section 2. Section 3 presents our zonal pricing model with storage. The main results of our zonal pricing analysis are discussed in Section 4. In Section 5 we present some model extensions and robustness results that focus on the effects of different storage technologies and locations, network characteristics, the variability of (renewable) energy supply, as well as lower demand elasticities. Finally, Section 6 concludes and highlights main policy implications.

2. Notation and economic quantities

As depicted in Fig. 1, storage facilities yield an inter-temporal connection between production and consumption, which are both additionally limited by the transmission capacities of the underlying electricity network. In particular, storage facilities may act as a consumer in one period and as a producer in a subsequent period. Before we explicitly state our zonal pricing model with storage, we first describe the economic quantities that are related to the four main functions of production, consumption, transportation, and storage. For the sake of completeness, all sets, parameters, and variables are summarized in Tables 4, 5 and 6 in the Appendix.

2.1. Electricity network and time horizon

Let us be given a set of discrete time periods T. We consider a graph $\mathcal{G} = (N, L)$ that is defined on a set of network nodes N and a set of transmission lines L. Each transmission line l is described by different technical characteristics including its maximal transmission capacity $\overline{f}_l$

[2] We note that assuming private investments in electricity storage that follow zonal price signals, the causality may change from effects of storage on the zonal design to effects of the zonal design on storage investment. However, as we do not explicitly model the investment behavior of market participants - which would be best captured by a multilevel market model (see Weibelzahl and Märtz (2017a)) - a detailed quantitative analysis of these effects will be out of the scope of this paper.