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,

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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 is, however, not the focus of this paper; see for instance Manwell and McGowan (1993), Glavin et al. (2008), or Tuohy and O'Malley (2009).

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. 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 item), 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 Figure 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.

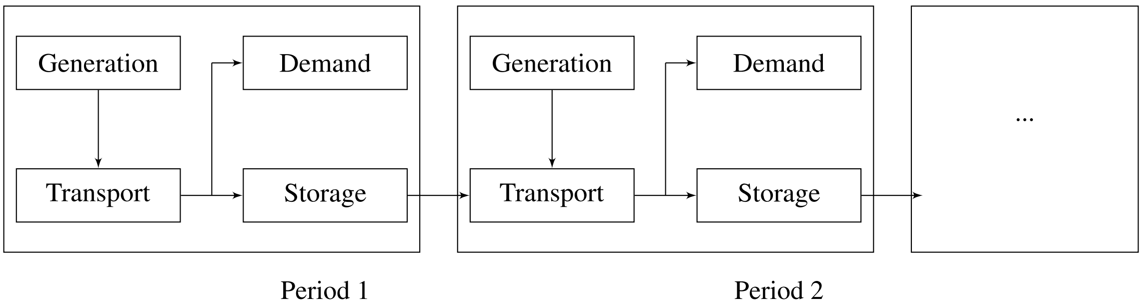

Figure 1: Inter-Temporal Market Structure with Storage

2.1. **Electricity Network and Time Horizon.** Let us be given a set of discrete time periods T. We consider a graph $\mathscr{G} = (N, L)$ 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 $\bar{f}_l$ and its susceptance B_l. Throughout the paper, power flows will be denoted by $f_{l,t}$.

In the context of zonal pricing, we further assume that the node set N is partitioned into k connected price zones. We refer to our node-set partition Z as a zonal configuration, with its elements describing the k different price zones $Z_1, \dots, Z_k$:

[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 - a detailed quantitative analysis of these effects will be out of the scope of this paper.

$$\emptyset \notin Z, \tag{1}$$

$$\bigcup_{i\in\{1,\ldots,k\}} Z_i = N, \tag{2}$$

$$Z_i \in Z, Z_j \in Z \text{ with } i \neq j \Rightarrow Z_i \cap Z_j = \emptyset. \tag{3}$$

In the case $k = 1$, we arrive at a single price zone system with a uniform electricity price. On the contrary, $k = |N|$ describes the nodal pricing case, where each node forms a separate zone.

2.2. **Electricity Demand.** Spot market demand $x_{n,t}$ is modeled by a continuous, strictly decreasing function $p_{n,t}$ for each node $n \in N$ and time period $t \in T$, i.e., we assume that each node has in each time period its own demand. In line with the vast literature on short-run congestion management including Chao and Peck (1996), Bjørndal and Jørnsten (2001), Bjørndal et al. (2003), Ehrenmann and Smeers (2005), Bjørndal and Jørnsten (2007), or Oggioni and Smeers (2013), we will use linear[3] demand functions in the main part of this paper, which is also in accordance with the growing literature on storage facilities; see, e.g., Sioshansi (2014). As pointed out by Bönte et al. (2015), in general spot market demand will not be totally inelastic. In particular, Bönte et al. (2015) estimated the average price elasticity of demand in the European Power Exchange day-ahead market for electricity with a value around -0.43, which may additionally justify the use of linear decreasing demand functions in contrast to completely inelastic demand.

As a main advantage, linear demand functions will allow to explicitly define

$$\sum_{t\in T}\sum_{n\in N}\int_0^{x_{n,t}} p_{n,t}(w)\mathrm{d}w$$

as the aggregated gross consumer benefit, which measures the sum of all monetary consumer gains. Observe that in the case of perfectly inelastic demand, welfare maximization would reduce to a minimization of system costs. In contrast to such a pure cost minimization, it is the aim of this paper to address the welfare effects of storage facilities in the context of different congestion management regimes.[4]

Note that the three-node network used in the remainder of this paper applies a comparatively price elastic demand, which may be a strong driver of the results. However, as we demonstrate in Section 5.5, our main qualitative insights remain consistent in a sensitivity analysis with lower demand elasticities.

2.3. **Electricity Generation.** Let G describe the set of all existing generation facilities, with $G_n \subset G$ denoting the generators located at node n. We will assume that each generator has constant variable production cost v_g and a prespecified generation capacity of $\bar{y}_g$. Production of a generator g in a time period t is given by $y_{g,t}$. Finally, the corresponding stepwise-linear supply function is denoted by $V_{g,t}$.

2.4. **Storage Facilities.** Similar to generation facilities, we assume a set of ex-ante given storage facilities S that may be charged or discharged in a period t. By $S_n \subset S$ we describe the subset of storage facilities located at node n. These storage facilities comprise different technologies including the well-known hydro pumped storage; see also Egré and Milewski (2002), Wicker (2004), or Figueiredo et al. (2006). However, as the latter may suffer from very limited locations together with relatively high infrastructure cost, our general setting will allow to apply the results for a variety of different storage technologies.

For each storage facility $s \in S$ we explicitly introduce the variables $z^+_{s,t}$ and $z^-_{s,t}$ that refer to the amount of electricity that is currently stored or discharged, respectively. In addition, we assume that all storage losses are captured by a (roundtrip) storage efficiency $\rho_s \in [0, 1]$, which measures the percentage of stored-in electricity that can be discharged in one of the subsequent periods. Analogously, we refer to $(1 - \rho_s)$ as the storage loss. Furthermore, $z_{s,t}$ gives the current storage level, i.e., the net storage level of s after charging and discharging in a period t. $\bar{z}^+_s$, $\bar{z}^-_s$, and $\bar{z}_s$ describe upper bounds on the three storage variables, which may possibly be infinite. Let us finally note that the effects of storage facilities on zonal pricing that are discussed in this paper can already be identified in a deterministic world without uncertainties. Therefore, we leave the analysis of the additional challenges of an uncertain demand or supply structure for future research.

[3]Note that applied studies use linear demand functions with slopes of down to 0.1 in absolute values.

[4]In the case of perfectly inelastic demand, additionally the problem of possibly non-unique equilibrium prices exists.

3. Zonal Pricing Model with Storage Facilities

Our paper builds on the frequently used ideal zonal pricing model introduced by Bjørndal and Jørnsten (2001) in the context of deregulated electricity markets; for the huge number of applications of this zonal pricing model we refer for instance to Bjørndal et al. (2003), Ehrenmann and Smeers (2005), Bjørndal and Jørnsten (2007), or Weibelzahl (2017). Even though the Scandinavian zonal pricing model is of second-best type in practice, the ideal zonal pricing model has originally been devoted to the Scandinavian system, where a benevolent transmission system operator is assumed to solve a benchmark zonal welfare-maximization power flow problem with feasibility as well as balancing constraints on demand and supply. Therefore, a socially optimal dispatch of generators with different price sensitive consumers being located throughout the network is modelled. In such a system, the complete physical network characteristics are taken into account, while nodal prices within a given zone are forced to be identical.[5] We explicitly add storage facilities to this standard model in order to analyze the effects of storage facilities on optimal price structures in an electricity network under zonal pricing and nodal pricing, respectively.

Note that in general storage facilities may be owned and controlled by different agents, e.g., generation firms, transmission system operators, or a stand-alone company. However, the assumption of a perfectly competitive market environment and a benevolent transmission system operator will yield the same optimal operational schedule for the given storage facilities independent of the concrete ownership structure. In particular, under our assumptions storage facilities will always be used in an efficient and welfare maximizing[6] way by either absorbing or injecting energy from/to the network.

Assuming fully competitive firms, we model zonal pricing as a welfare maximization problem, where welfare is given by the aggregated difference between consumer benefit and all production costs (see also Grimm et al. (2016a) or Grimm et al. (2016b)):

$$W(x,y,z) := \sum_{t\in T}\sum_{n\in N}\left(\int_0^{x_{n,t}} p_{n,t}(w)\,\mathrm{d}w - \sum_{g\in G_n} v_g y_{g,t}\right). \tag{4}$$

Allowing storage facilities to be charged $z^+_{s,i}$ and discharged $z^-_{s,i}$, at any time $t \in T$ the current storage level is described by:

$$z_{s,t} = \sum_{i=1}^{t} \rho_s z^+_{s,i} - \sum_{i=1}^{t} z^-_{s,i} \qquad \forall s \in S, t \in T. \tag{5}$$

Note that on the right-hand side of the above constraint the storage efficiency ρ_s directly determines the storage loss and the net amount of electricity that can be stored.

Given these storage restrictions, Kirchhoff's First Law ensures power balance at every node

$$x_{n,t} = \sum_{g\in G_n} y_{g,t} + \sum_{l\in\delta_n^{\text{in}}(L)} f_{l,t} - \sum_{l\in\delta_n^{\text{out}}(L)} f_{l,t} + \sum_{s\in S_n} z^-_{s,t} - \sum_{s\in S_n} z^+_{s,t} \qquad \forall n \in N, t \in T, \tag{6}$$

where $\delta_n^{\text{in}}(L)$ and $\delta_n^{\text{out}}(L)$ describe the set of in- and outgoing lines of node $n \in N$. In the simplest case of a capacity-constrained power flow model, only the maximal (and minimal) transmission capacities of the respective transmission lines limit power flows $f_{l,t}$ on each line:

$$-\overline{f}_l \le f_{l,t} \le \overline{f}_l \qquad \forall l \in L, t \in T. \tag{7}$$

[5] Alternatively, some form of the above-mentioned second-best zonal pricing may be applied, where (i) cross-border capacities are aggregated into inter-zonal trade limits and (ii) the intra-zonal topology of the network is neglected. As such an approach typically yields infeasibility of power flows, second-best zonal pricing is often accompanied by redispatch. Even though redispatch has been investigated for the no-storage case (see also the literature review Weibelzahl (2017)), the inclusion of storage facilities into the redispatch market will yield severe difficulties for the organization and implementation of redispatch. In particular, under the assumption of cost-based redispatch, the definition of (profit-neutral) redispatch prices for storage facilities that are called on the redispatch market is not straightforward. As one main reason, forgone profits of a currently redispatched storage facility will highly depend on future market prices, which in turn are influenced by the current redispatch intervention. As another main challenge, under second-best zonal pricing the determination of net or available transfer capacities (NTCs or ATCs) between the different price zones comes on top of the definition of zonal boundaries. Obviously, both the chosen zonal configuration and the used NTCs will influence the effectiveness of second-best zonal pricing to a large extent. Given this additional complexity and the overall length of our article, the topic of second-best zonal pricing is therefore left for in-depth and careful future research.

[6] Even though the analysis of market power is not the focus of this paper, future research could analyze the discussed effects for the case of storage owners that act strategically. In such a setting different owners may have an incentive to use storage facilities in a socially inefficient way in order to increase their individual profits.

In a more complex DC model – as used in this paper – power flows $f_{l,t}$ on each line l are additionally characterized by Kirchhoff's Second Law, which links power flows to phase angles:

$$f_{l,t} = B_l\left(\Theta_{n,t} - \Theta_{m,t}\right) \qquad \forall l = (n,m) \in L, t \in T. \tag{8}$$

In order to ensure unique phase angle values, we set the respective value of the reference node 1 to zero:

$$\Theta_{1,t} = 0 \quad \forall t \in T. \tag{9}$$

Applying zonal pricing, we require any pairwise different nodes (n, m) in a given zone $Z_i \in Z$ to have identical zonal prices. Assuming elastic demand functions, this can be formulated as follows:

$$p_{n,t} = p_{m,t} \qquad \forall i \in \{1,\ldots,k\}, \{(n,m) : n, m \in Z_i, n < m\}, t \in T. \tag{10}$$

Note that in the case $k = 1$, all nodes will have an identical price, which implies a uniform pricing system. In its other extreme, $k = |N|$ yields a nodal pricing system, where all prices may possibly differ.

In addition to the above price equality, under zonal pricing at each node consumers and producers must face an identical price[7]

$$p_{n,t} = V_{g,t} \qquad \forall n \in N, g \in G_n, t \in T. \tag{11}$$

We finally impose some simple variable bounds. In particular, we assume that all storage level, charging, and discharging variables are always nonnegative and do not violate their upper bounds:

$$0 \le z_{s,t} \le \bar{z}_s, \quad 0 \le z^+_{s,t} \le \bar{z}^+_s, \quad 0 \le z^-_{s,t} \le \bar{z}^-_s \qquad \forall s \in S, t \in T. \tag{12}$$

Furthermore, consumption can not take negative values

$$0 \le x_{n,t} \qquad \forall n \in N, t \in T, \tag{13}$$

while production $y_{g,t}$ must also be nonnegative and not exceed its given generation capacity:

$$0 \le y_{g,t} \le \overline{y}_g \qquad \forall n \in N, g \in G_n, t \in T. \tag{14}$$

Let us note that zonal pricing is a restriction of nodal pricing, since additional price constraints are added. Analogously, a zonal pricing system with k zones is a relaxation of a zonal pricing model with fewer zones, if additional zones are constructed by splitting existing zones; see also Bjørndal and Jørnsten (2001).

We conclude this section by observing that under perfect competition the introduction of a storage facility in a transmission network can never be welfare-diminishing. As a main reason, in the case of a storage that destroys welfare, the benevolent transmission system operator will refrain from charging the storage. Ultimately, this yields the same welfare as in the no-storage case.

4. On the Effects of Storage Facilities on Optimal Pricing in Electricity Networks

4.1. **Three-Node Network.** In this paper we consider a three-node network that comprises two northern nodes indexed by 1 and 2 as well as a southern node 3. In order to keep our analysis as simple as possible and to ensure an intuitive explanation of the main effects of storages on optimal zonal pricing, in a first step we only assume two transmission lines: The northern link connects node 1 with node 2 and the north-south line transports electricity between node 2 and node 3. As shown in Figure 2, the two lines both have a transmission capacity of 75 MWh. Observe that in Section 5 we also analyze network effects, where losses and more complex loop flows are considered.

At the three nodes we further assume a capacity-constrained generator with variable production cost of 30 €/MWh, 32.5 €/MWh, and 57.5 €/MWh, respectively. These variable cost imply a regional generation structure that is characterized by a relatively high cost level in the south as compared to the north.

Additionally, in line with Section 2, we consider linear demand functions at the three nodes. In particular, we assume that for any given electricity price, demand at the two northern nodes is always lower than demand at the southern node. Considering only two different time periods, we assume that periods 1 and 2 are the off-peak (low demand) and on-peak (high demand) period, respectively. Observe that we assume identical slopes at the different network nodes and in the two time periods. This directly implies that the price elasticity of demand simplifies for a given price $p_{n,t}$ to

$$\varepsilon_{n,t} = -\frac{p_{n,t}}{a_{n,t} - p_{n,t}} \qquad \forall n \in N, \ t \in T.$$

Ultimately, under a given price $p_{n,t}$ the elasticity is only influenced by the intercept of the demand function. In particular, a demand function with a large intercept that indicates a high demand (like in the south or in

[7] Note that in the case of a meshed network with relatively few zones as compared to the number of network nodes, it may be difficult to find feasible solutions if producer and consumer prices must be identical within each zone. Therefore, one may alternatively formulate this price relation as an inequality.

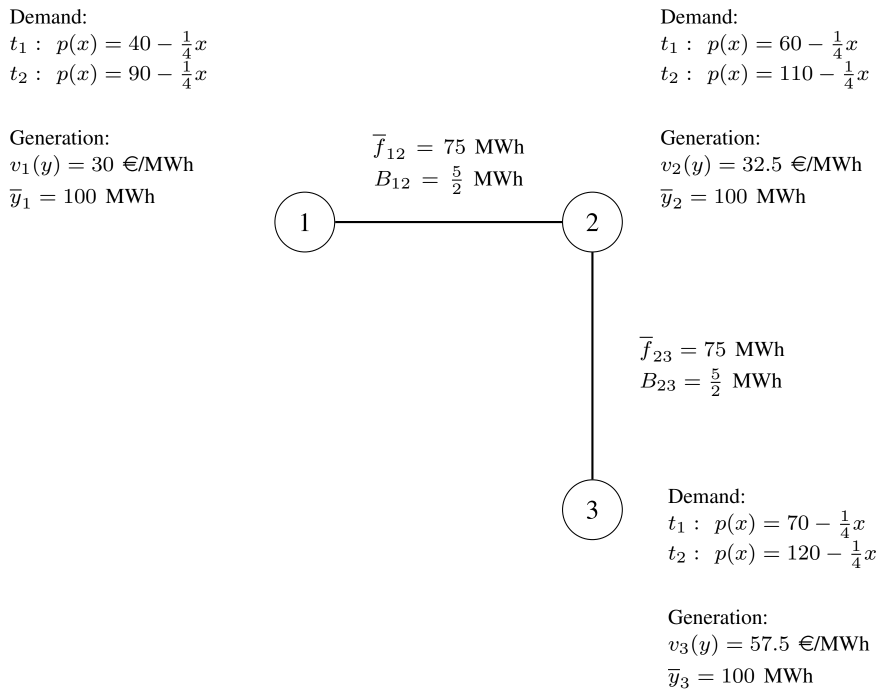

Figure 2: Three-Node Network

period 2) will in general be characterized by a comparatively high flexibility under the considered price of $p_{n,t}$. More detailed information on the used demand functions can be found in Figure 2.

We note that the assumed demand-generation pattern may be interpreted as a very simplified model of the German electricity market, where (i) generation cost in the north are relatively low given the installed wind turbines and (ii) demand in southern Germany is higher as compared to the northern nodes.

In order to evaluate and quantitatively assess the effects of market designs on the different economic players, we decompose welfare into net consumer rent (CR), producer rent (PR), transmission rent (TR), and storage rent (SR):

$$W(x,y,z) \overset{(4)}{=} \sum_{t \in T} \sum_{n \in N} \left(\int_0^{x_{n,t}} p_{n,t}(w) \, \mathrm{d}w - \sum_{g \in G_n} v_g y_{g,t} \right) \overset{(6)}{=} CR + PR + TR + SR, \tag{15}$$

with

$$\begin{aligned} CR &:= \sum_{t \in T} \sum_{n \in N} \left(\int_0^{x_{n,t}} p_{n,t}(w) \, \mathrm{d}w - x_{n,t} p_{n,t} \right), \\ PR &:= \sum_{t \in T} \sum_{n \in N} \sum_{g \in G_n} y_{g,t} (p_{n,t} - v_{g,t}), \\ TR &:= \sum_{t \in T} \sum_{l=(n,m) \in L} (p_{m,t} - p_{n,t}) \, f_{l,t}, \\ SR &:= \sum_{t \in T} \sum_{n \in N} \sum_{s \in S_n} \left(z_{s,t}^{-} - z_{s,t}^{+} \right) p_{n,t}. \end{aligned}$$

CR is defined as the aggregated gross consumer benefit minus all consumer payments, PR is given by aggregated revenues of the generators minus all production costs, TR is given by the price difference of the two end nodes of a transmission link multiplied by the respective network flow, and SR is described as the difference between revenues from selling the discharged electricity minus costs for buying the charged electricity.

4.2. **Nodal Pricing.** In this section we discuss the nodal pricing solution[8], which may alternatively be interpreted as optimal zonal pricing with flexible boundaries in the different periods.

[8] All results were calculated using the optimization software SCIP; see Achterberg (2009).

TABLE 1. Results of the Three-Node Network

Pricing System	Storage	CR	PR	TR	SR	W	υ^{reg}	υ^{temp}
nodal	no	6714.57	13125	1312.5	-	21152.08	12.20%	49.22%
	yes	9847.35	11278	2708.25	0	23833.41	19.07%	23.64%
zonal ($p_1 = p_2$)	no	6752.07	13000	1312.5	-	21064.58	13.53%	49.39%
	yes	9691.66	10345	-1362.57	3892.25	22566.34	21.87%	37.13%
zonal ($p_2 = p_3$)	no	5739.56	14375	212.5	-	20327.08	13.89%	43.39%
	yes	7872.97	12514	1726.37	1414.67	23527.82	18.77%	27.77%

4.2.1. *The No-Storage Case.* Let us first consider the no-storage case; see also Figure 3. As generator 1 has the lowest variable cost in the complete network, it produces at full capacity already in the off-peak period. Obviously, only 75 MWh of the production at node 1 can be transported to the other two nodes, which are both higher demand nodes. The remaining 25 units are directly consumed at node 1. Given that the generation capacity of generator 1 is binding, at node 1 the nodal price of 33.75 €/MWh exceeds its variable cost of 30 €/MWh. Turning to the second node, also generation capacities at node 2 are fully utilized with a production of 100 MWh. The produced electricity is directly consumed at node 2 with a nodal price of 35 €/MWh that again exceeds variable production cost. Given its relatively low off-peak demand, at the southern node 3 the variable generation cost are too high to allow for a profitable production. Therefore, southern demand is exclusively served by production of node 1, which is transported to the south via node 2. Southern consumption in the amount of 75 MWh implies a nodal price of 51.25 €/MWh. Observe that the three nodal prices differ at each node, which yields an optimal three-zone configuration in period 1.

In the high-demand period 2, now it is profitable for all three generators to produce at full capacity. As generator 3 serves parts of the local demand at node 3, network flows of the two transmission lines – that were previously fully utilized – now fall under their maximal transmission capacity. This directly implies a uniform price of 81.67 €/MWh in the on-peak period. Note that even though transmission capacities are non-binding, the fully utilized generation capacities imply a uniform system price that exceeds the highest variable cost of generator 3. Total welfare amounts to 21152.08 €.

4.2.2. *The Storage Case.* Now consider the case of a storage facility that is located at node 2. The assumed storage has an unlimited capacity and an efficiency of 90 percent, which may be interpreted as some kind of large battery storage; see also Section 5 for an analysis of different roundtrip efficiencies and constrained storage capacities.

As the northern transmission line connecting node 1 and node 2 is already congested in the no-storage case, in period 1 there is no need to adjust either consumption or production at node 1 in order to store at node 2 any electricity that is produced at node 1. Instead, consumption at node 2 and node 3 are reduced to 10 MWh and 50 MWh, respectively. As the reduced demand at node 2 and node 3 yields a price increase at these eastern nodes, it is now profitable for generator 3 to produce 67.1 units. Given this southern production pattern, 17.10 units of the southern production at node 3 are transmitted to node 2, where it is directly stored. Observe that in contrast to the northern link (1,2), the capacity of the north-south link (2,3) is non-binding. This implies an east-west, two-zone price configuration in period 1. Note that in the eastern zone the corresponding price is equal to the variable cost of the most expensive generator at node 3, whose capacity is not fully utilized.

In period 2 again all three generators produce at their full capacity. However, discharging the storage facility at node 2 allows to increase consumption at all three nodes as compared to the no-storage case. As the southern node 3 is the high-demand node in the system, the north-south line (2,3) is now fully utilized in order to transport 75 units of the discharged electricity at node 2 to node 3. Only 4.44 units of the discharged electricity are transmitted to node 1 via the northern link (1,2). Given that transmission between the two northern nodes does not reach the transmission capacity of 75 MWh, we observe a north-south splitting with a total welfare of 23833.41 €.

As expected, the introduction of a storage facility yields indeed an increase in welfare of almost 13 percent. From a policy perspective, this underlines that storage facilities should be integrated in the market clearing in order to realize possible efficiency gains. Furthermore, the storage reduces the inter-temporal price variance υ^{temp} from 49.22 percent to 23.64 percent, with the price variance being measured by the standard variation coefficient. However, the storage facility also affects transmission flows, which in turn changes inter-regional price differences. In the discussed example the inter-regional price variance υ^{reg} increases from 12.20 percent to 19.07 percent, where the variance is again measured by the standard variation coefficient; see also the two last columns in Table 1. This new price structure ultimately implies a new optimal zonal decomposition of the electricity network as compared to the no-storage case:

Result 1 (Nodal Pricing with Storage Facility)**.** *Under nodal pricing, storage facilities may influence both the absolute value of transmission flows and their direction. The changed transmission flows may directly translate in new nodal prices with an increased inter-regional price variance. In turn, an increase in the inter-regional price variance may imply a new optimal zonal decomposition of the energy system as compared to the no-storage case.*

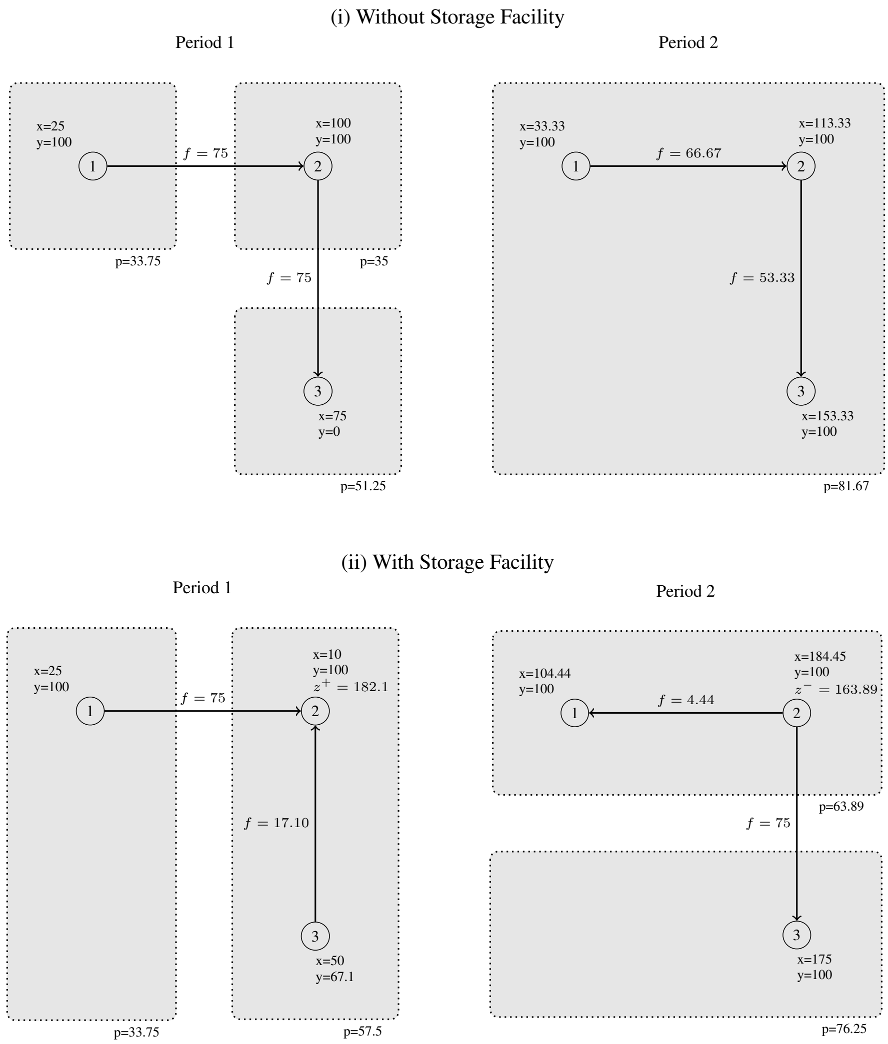

Figure 3: Nodal Pricing Solution

4.3. **Zonal Pricing.** In this section we consider the case of a fixed-zone system with two price zones, i.e., we analyze the situation where in both periods a north-south and an east-west zonal configuration is implemented, respectively.

4.3.1. *Comparison of Different Zonal Designs.*

The No-Storage Case. Let us first consider the no-storage case with a *northern and a southern* price zone; see also Figure 4. Recall that under nodal pricing the two northern nodes 1 and 2 were characterized by different prices of 33.75 €/MWh and 35 €/MWh, respectively. In order to ensure a single price in the northern zone, consumption at node 2 must be increased by 5 MWh, which yields a reduced price at node 2 of only 33.75 €/MWh. This ensures the same price as at node 1. In turn, the increased consumption at node 2 directly implies that only 70 units of the northern production can be transported to the southern node 3. As production is again not profitable at the southern node 3 in the off-peak period, southern consumption is reduced to 70 MWh, with a price of 52.5 €/MWh.

Since the solution of the nodal pricing system with no storage yields a uniform price in the on-peak period, the results of the previously discussed nodal pricing model are identical to the north-south zonal pricing model in period 2, i.e., the two solutions coincide. Welfare aggregated over both periods amounts to 21064.58 €; see Table 1.

Now consider the *east-west* price zone configuration; see also Figure 5. Note that under nodal pricing the two eastern nodes had nodal prices of 35 €/MWh and 51.25 €/MWh in period 1, respectively. As a reduction in consumption at node 3 only increases the price difference between node 2 and node 3, in the case of an east-west splitting, consumption at node 2 is therefore decreased until the two eastern nodes have an identical zonal price. In turn, the reduced consumption in the eastern zone implies a decreased production at node 1 (western zone), where at the same time consumption can be raised to 40 MWh. As generator 1 is not producing at full capacity, the western-zone price falls to its variable production cost of 30 €/MWh.

Applying the same arguments as under a north-south splitting, in period 2 we again arrive at the optimal nodal pricing solution in the east-west configuration. Welfare amounts to 20327.08 €.

As we would also expect for the German electricity market with a high-demand center in southern Germany (see for instance Egerer et al. (2015) or Grimm et al. (2015)), welfare under the east-west configuration decreases as compared to the north-south splitting. In particular, in our example we observe under the east-west splitting a welfare loss of nearly 4 percent as compared to the north-south configuration. This decrease is mainly driven by the high demand reduction at node 2 under the east-west splitting, which corresponds to a reduction in consumer rent from 6752.07 € to 5739.56 €; see Table 1.

The Storage Case. We now consider the same storage facility as under nodal pricing that is located at node 2. Let us first analyze the situation of a *north-south* splitting. In order to ensure a single northern-zone price in period 1, consumption at node 2 is raised to 105 MWh. Additionally, in contrast to the nodal pricing solution the amount of stored electricity is reduced to 137.9 MWh. At node 2 the consumed and the stored electricity are satisfied by all three generators, with 75 units being transported to node 2 from node 1 and 67.9 units being transmitted from node 3. As compared to the nodal pricing solution, the new demand-generation pattern implies that the flow on the north-south link (2,3) increases. In turn, the increased flow yields a slightly reduced consumption level in the south, with the generator at node 3 now producing at full capacity. Given this binding generation capacity in the south, the corresponding southern zone price of 61.98 €/MWh exceeds variable production cost at node 3 of 57.5 €/MWh.

Again, in period 2 all three generators produce at full capacity. Since less electricity was stored in period 1 as compared to the nodal pricing solution, consumption is slightly decreased at the two northern nodes. Total welfare amounts to 22566.34 €; see Table 1.

Even though under nodal pricing we can already observe an *east-west* splitting in period 1 (but not in period 2), under a fixed east-west-splitting in both periods we arrive at a different solution as compared to the nodal pricing model. The reason behind this effect is that the stored amount in period 1 must be adjusted in a way that also ensures an east-west splitting in period 2. In particular, the amount of stored electricity is reduced at node 2 in period 1, which in turn implies a production reduction at node 3 as compared to both nodal pricing and the north-south splitting.

In period 2 the reduced amount of stored electricity yields a reduction in consumption at node 2 as compared to nodal pricing. Production and consumption at node 1 and node 3 are identical to the nodal pricing solution. Even though consumption at node 2 is decreased, as compared to the north-south splitting the reduced generation cost in period 1 yield a welfare of 23527.82 €. In line with this observation, producer rents under the east-west splitting increase from 10345 € to 12514 €; see Table 1.

The discussed example underlines that even though in the no-storage case a north-south splitting is optimal, in the presence of a storage facility at node 2, the optimal zonal choice is an east-west decomposition. As a main reason, storage facilities do not only yield a reduced inter-temporal price variance, but also affect transmission flows in a way that completely change the price structure. In particular, the inter-regional price variances υ^{reg} increase in the presence of storage facilities; see also the second-last column in Table 1. Ultimately, this requires a reconfiguration of optimal price zones. We summarize these observations in the following energy-policy relevant result, which calls for a careful analysis of price zone configurations in times of increased storage facility investments:

Result 2 (Zonal Pricing with Storage Facility). *Similar to nodal pricing, storage facilities influence transmission flows under zonal pricing, which may increase inter-regional price variances. The new price structure may imply a new optimal zonal decomposition as compared to the no-storage case, i.e., for a given number of price zones the best zonal boundaries may change with the introduction of storage.*

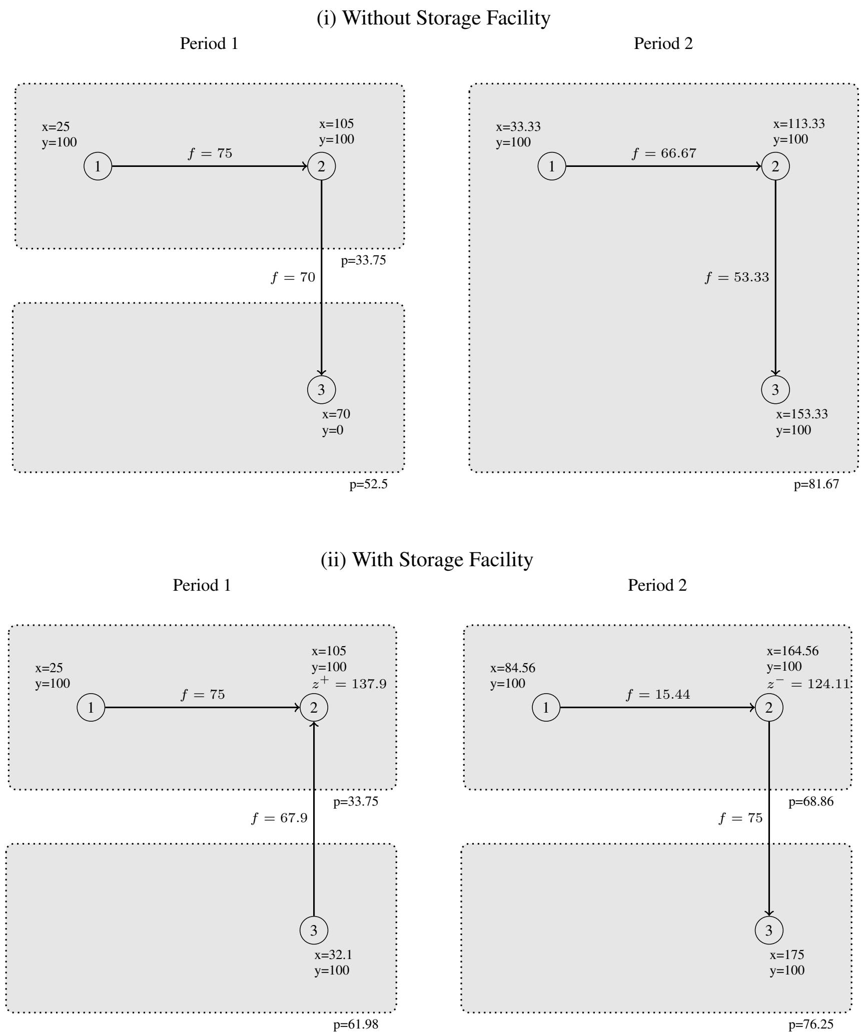

Figure 4: Zonal Pricing Solution for $p_1 = p_2$

4.3.2. *Incentive Effects.* In the discussed storage example, as compared to the sub-optimal north-south splitting, producers experience an increase in their rents under the optimal east-west configuration. In contrast, consumers have an incentive to realize or keep the sub-optimal north-south decomposition, which is the optimal zonal design in the no-storage case. Note that the same is true for storage facilities, whose rents decrease from 3892.25 € under the north-south configuration to only 1414.67 € under the optimal east-west configuration. This underlines that the implementation of optimal price zone configurations may not always be a pareto improvement for all market participants; see Table 1 for an overview of the corresponding rents. Therefore, an increased investment in storage facilities that is currently observed in many real-world electricity markets may be accompanied by severe conflicts of interest regarding an optimal zonal design. In particular, incentives may be aligned in a way that result in a zonal configuration that is associated with a welfare loss. In addition, if policy-makers aim at fostering storage facility investments, there may be a trade-off between a welfare maximizing zonal design and a zonal composition with maximal storage rents that will provide increased investment incentives for storage facility owners in the long-run. Even though a detailed analysis of long-run investment effects is out of the scope of this paper, under zonal pricing the storage rents in Table 1 indicate that the needed investments can at least be financed for per-unit storage investment costs of up to $\frac{SR}{z^+}$. In our case these values amount to 28.23 €/MWh and 11.13 €/MWh for the north-south and east-west zonal design, respectively.

Note that even though the inclusion of storage facilities does in general not result in optimal zonal configurations benefitting every stakeholder, similar results are also well-known for other spatial re-definitions of zonal boundaries. In particular, Bjørndal and Jørnsten (2001) already highlighted possibly conflicting interests among market participants concerning an optimal zonal design for the no-storage case. However, given its importance, we summarize these problematic acceptance problems that also prevail in the presence of storage in the following policy-relevant result:

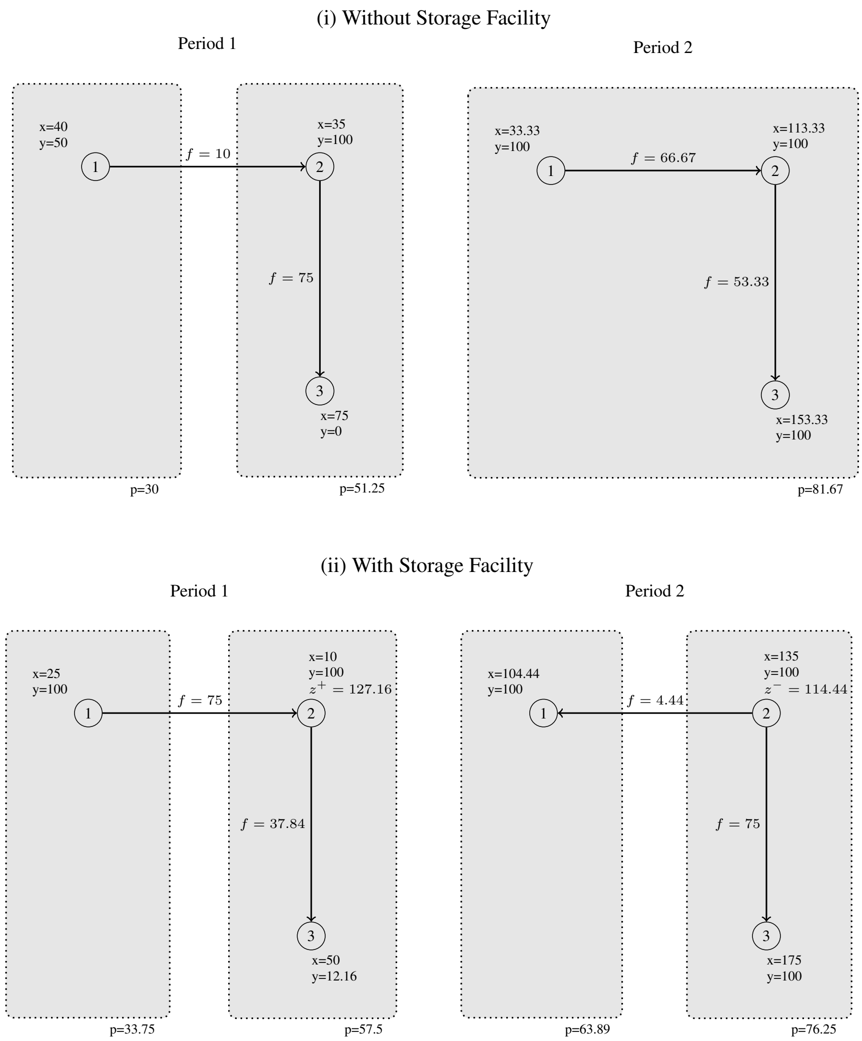

Figure 5: Zonal Pricing Solution for $p_2 = p_3$

Result 3 (Incentive Problems)**.** *In the presence of storage facilities (some) market participants may have an incentive to realize or keep a sub-optimal zonal configuration, which may be an optimal splitting in the no-storage zonal pricing model.*

4.3.3. *How to Determine Optimal Zonal Boundaries?* From a practical point of view it is not only crucial to decide, whether a given zonal composition is superior than another zonal design. Instead, methods to detect optimal zonal boundaries are of high importance. However, as already pointed out for the no-storage case (see for instance Stoft (1996), Stoft (1997), Bjørndal and Jørnsten (2001), Breuer et al. (2013), Wawrzyniak et al. (2013), or Grimm et al. (2016a)), established criteria to determine optimal price zones may also fail in the presence of storage facilities. To give a short example, consider the criterion of congested transmission flows under nodal pricing. Recall that in the nodal pricing solution with storage only the northern line is congested in period 1, while in period 2 only the north-south line has a binding capacity. Given this ambiguity, the criterion of congested transmission lines does not give any hint regarding an optimal zonal choice in the case of a storage facility. Therefore, in general congested lines of a nodal pricing solution may not be used as a valuable criterion to determine an optimal fixed-zone pricing system. Note that similar problems may be identified for other simple, heuristic criteria used to detect optimal zonal boundaries:

Result 4 (Established Criteria to Determine Optimal Zonal Boundaries)**.** *Established criteria like congested transmission lines of a nodal pricing system may fail in determining optimal zonal boundaries in the presence of storage facilities.*

Given the described failure of simple zonal-configuration criteria, we finally propose an extension of our zonal pricing model introduced in Section 3 that allows for an endogenous determination of an optimal zonal design in the presence of storage facilities. From a policy perspective, such a model may be used to evaluate and assess the economic effects of different zonal designs in order to being able to implement an efficient zonal system.[9]

For this reason, consider a set of (politically) relevant zonal configurations C that satisfy the connectivity conditions (1) to (3). We introduce for each $c \in C$ a binary variable σ_c that indicates whether or not zonal design c is chosen as the optimal zonal configuration. Obviously, only one zonal design can be implemented:

$$\sum_{c \in C} \sigma_c = 1. \tag{16}$$

In addition, if a zonal design is chosen, prices at the nodes belonging to a respective zone must be equal

$$p_{n,t} - p_{m,t} \leq M(1 - \sigma_c), \quad p_{n,t} - p_{m,t} \geq -M(1 - \sigma_c), \tag{17}$$

for all $c \in C, i \in \{1, \ldots, k_c\}, \{(n,m) : n, m \in Z_i, n < m\}, t \in T$. In the above equation, M denotes a large constant, which is commonly referred to as "big-M". With these notations, the resulting endogenous price zone configuration model is equal to the welfare maximizing zonal pricing problem introduced in Section 3, where the endogenous price zone constraints (16) and (17) replace the standard zonal pricing relation in Equation (10).

We finally note that using this mathematical formulation on how to make the division of network nodes into price zones endogenous, in line with the presented results of the three-node network, our extended model identifies again the north-south splitting as the optimal zonal configuration in the no-storage case, while the east-west zonal division is optimal in the presence of a storage facility at node 2. Even though for the discussed simple network structure the identification of an optimal zonal design can alternatively be done manually by enumerating all the relevant zonal candidates (in our case there are only two candidates), in general our model extension will be a valuable tool for an in-depth analysis of consistent and efficient definitions of zones for real-world electricity markets without enumerating all zonal candidates. In particular, our model extension may for instance be used as a first evaluation of the effects of an introduction of two price zones in Germany (with a North-German zone and a South-German zone), which is currently discussed in the context of increasing investments in storage facilities and a growing share of renewable energy. Obviously, suboptimal zonal configurations may be accompanied by severe welfare-losses and may also yield wrong investment signals in the long-run; see for instance Grimm et al. (2016b) or Weibelzahl (2017).

5. Extensions and Robustness Results

In this section we discuss some model extensions and present robustness results. In particular, we analyze the effects of

- different storage technologies (Section 5.1),
- network characteristics (Section 5.2),
- variable (renewable) energy supply (Section 5.3),
- different locations of the storage facility within the transmission network (Section 5.4), and
- a lower demand elasticity (Section 5.5).

5.1. **Different Storage Technologies.**

5.1.1. *Impact of Storage Efficiencies.* Engineers developed various types of storage technologies that are typically characterized by different technical parameters. Obviously, different technology-specific characteristics may limit the use of storage facilities, which in turn may have an effect on equilibrium prices. Storage facilities may for instance be described by different degrees of storage losses; see, e.g., Walawalkar et al. (2007) or Pehnt and Höpfner (2009). Therefore, in Figure 6(i) we analyze the economic effects of different degrees of storage efficiencies. We focus on the east-west and the north-south zonal pricing configurations and present the respective welfare level for different efficiencies. The results indicate that similar to our reference example with a loss of 10 percent, the east-west zonal design is "better" in terms of welfare for efficiency levels between 60 and 100 percent. Only for storage efficiencies of less than 60

[9] Our model extension may be (re)interpreted as some kind of bilevel problem, where on the first level a regulator or transmission system operator chooses a welfare maximizing zonal configuration of the grid. The regulator anticipates competitive market outcomes under the realized zonal design, where this second level problem is described by our standard zonal market model introduced in Section 3. Note that under a benevolent planner and perfectly competitive firms, the objective functions of the described two problem levels will both correspond to a maximization of welfare. From a mathematical point of view, identical (welfare) objectives on the two levels directly imply that the discussed hierarchical model may be reformulated and solved as a single-level welfare maximization problem, where the decisions on an optimal zonal design and on corresponding zonal market clearing are made in an integrated setting. Ultimately, this implies that our endogenous zonal configuration model can be obtained by only extending our standard zonal pricing model of Section 3 by some kind of endogenous zonal configuration constraints.

percent the north-south decomposition yields higher welfare levels. The main reason for this change in the optimal zonal design is the fact that storage facilities with an efficiency of less than 60 percent cause too high losses to be profitably used in the east-west splitting. This underlines that despite the fact that the discussed results are robust within some reasonable parameter interval and may therefore be generalized to different storage technologies, the given physical characteristics of storage may affect optimal zonal boundaries in a general setting. In addition, we see that even though storage facilities add losses to the electricity system, for reasonable storage loss factors there will still be an overall efficiency gain for the market as compared to the no-storage case.

5.1.2. *Impact of Storage Capacities and Minimum Storage Levels.* In analogy to the case of different storage efficiencies, in Figure 6(ii) we consider different storage capacities. Obviously, except from the limit case of zero capacity (no-storage case), the east-west zonal design is always welfare superior as compared to the north-south case. In addition, for both zonal configurations welfare increases with the storage capacity until it is not binding anymore (the unlimited case). At least under free storage facilities with no market power this finding highlights that storage facility investments may be a tool for policy-makers to increase the overall efficiency of the electricity system. However, even though we observe a welfare increase with positive storage rents of 3892.25 € and 1414.67 € under the two zonal designs (see also Table 1 and our comments in Section 4.3.2), future work that takes storage facility investment costs of different technologies into account must analyze, whether these rents are large enough to justify the investments needed.

Finally, Figure 6(iii) depicts the effects of minimum storage levels, i.e., lower bounds on the stored content. Such minimum storage levels may be interpreted as some kind of a depth of discharge; see for instance Guena and Leblanc (2006), Ibrahim et al. (2008), or Rahman et al. (2012). As can be seen from our analysis, for reasonable minimum storage levels all results of our zonal analysis are robust. However, as additional (and possibly unnecessary) electricity must be stored, welfare decreases with an increasing minimum storage level that may technically be required.

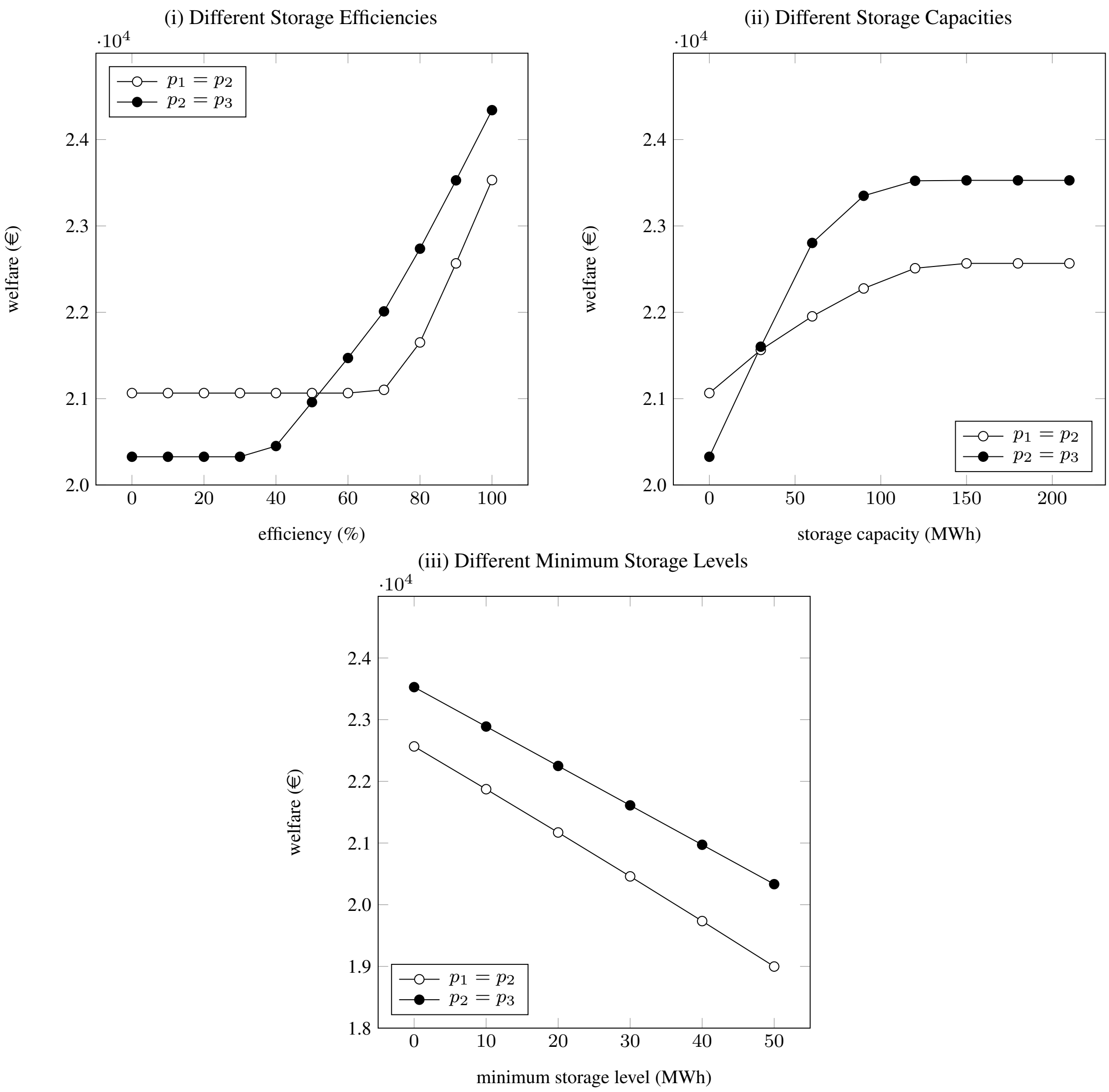

Figure 6: Effects of Different Storage Technologies

5.2. **Network Characteristics.**

5.2.1. *Impact of Transmission Losses.* In a more general setting, transmission lines may additionally be characterized by losses; see already the seminal paper on optimal pricing in electricity networks by Bohn et al. (1984). Recall that in Section 2 we introduced our loss-less DC power flow model, where transmission lines were exclusively characterized by their susceptance and their transmission capacity. As it is well known, underlying losses are inherently non-linear and require the inclusion of additional physical quantities. In order to keep our analysis as simple as possible, in this section we consider a simplified approach to network losses based on Bohn et al. (1984) or Kirschen and Strbac (2004). In particular, we assume that all losses are captured by a quadratic function $\mathscr{L}_{l,t} = K_l f_{l,t}^2$ of the power flow $f_{l,t}$ on a line l, where K_l describes the normalized line resistance; for more details on K_l see Kirschen and Strbac (2004).

As can be seen in Figure 7, in line with our expectations, a higher resistance yields a decreased welfare for all considered model variants. Our analysis underlines that the resistance and the corresponding transmission losses are indeed nonlinearly related to welfare in both the storage and no-storage case. Note that similar nonlinearities were already highlighted in the literature for the no-storage case; see for instance Hirst and Kirby (2001). In addition, the optimality of the north-south splitting in the no-storage case and the optimality of the east-west splitting in the presence of a storage facility are also valid for a network with losses - except for very high resistance values. Therefore, the main intuition of our results can also be applied to networks with transmission losses.

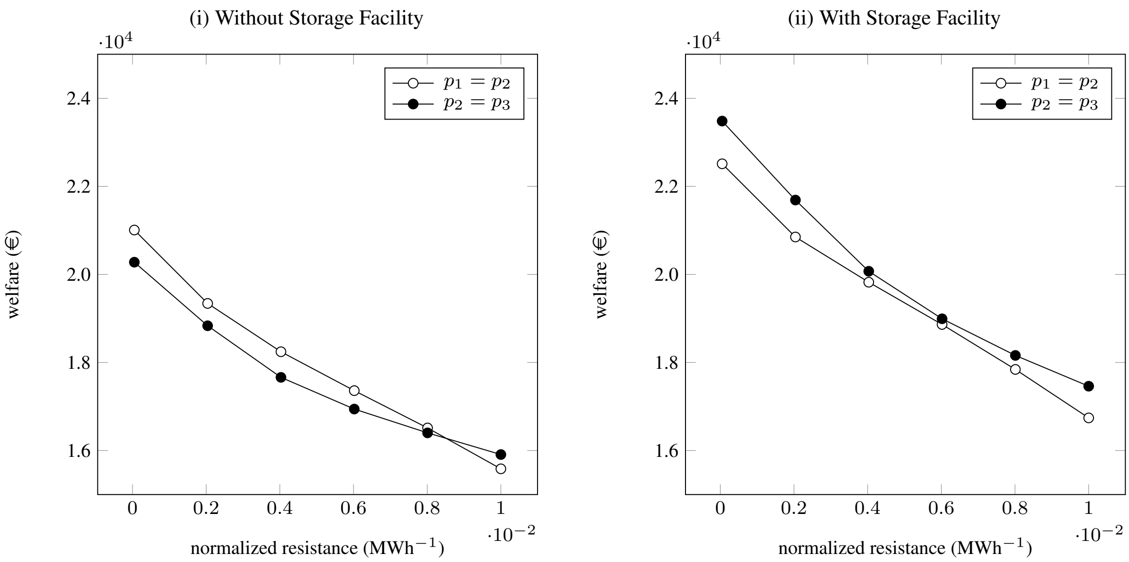

Figure 7: Effects of Quadratic Transmission Losses

5.2.2. *Impact of Transmission Capacities.* In this section we focus on different transmission capacities of the network. As depicted in Figure 8(i), for the no-storage case an increase in the transmission capacity of the two lines ultimately yields a uniform pricing system. This can be seen, as for transmission capacities of more than 125 MWh, capacity restrictions of the network are not binding anymore. In contrast, in the presence of a storage facility, a network where transmission capacities are "large enough" does not yield a uniform pricing system; see Figure 8(ii). Again, this highlights that storage may increase the inter-regional price differences of a market, which may ultimately change the optimal number of price zones as compared to the no-storage case (single-zone vs. two-zone design).

As can be seen from Figure 9, interestingly additional transmission capacities will not automatically lower the use of storage. In contrast, an increase in the transmission bounds allows a more efficient use of the available storage technology at node 2. Therefore, the relationship between storage and transmission must not always be conflicting, but can also be complementary. In particular, a joint planning of storage and transmission capacities may yield a higher welfare increase as compared to a pure extension of either storage or transmission capacities. From a policy perspective, this underlines that these two planning dimensions should jointly be addressed and not be reduced to a simplified question regarding transmission vs. storage.

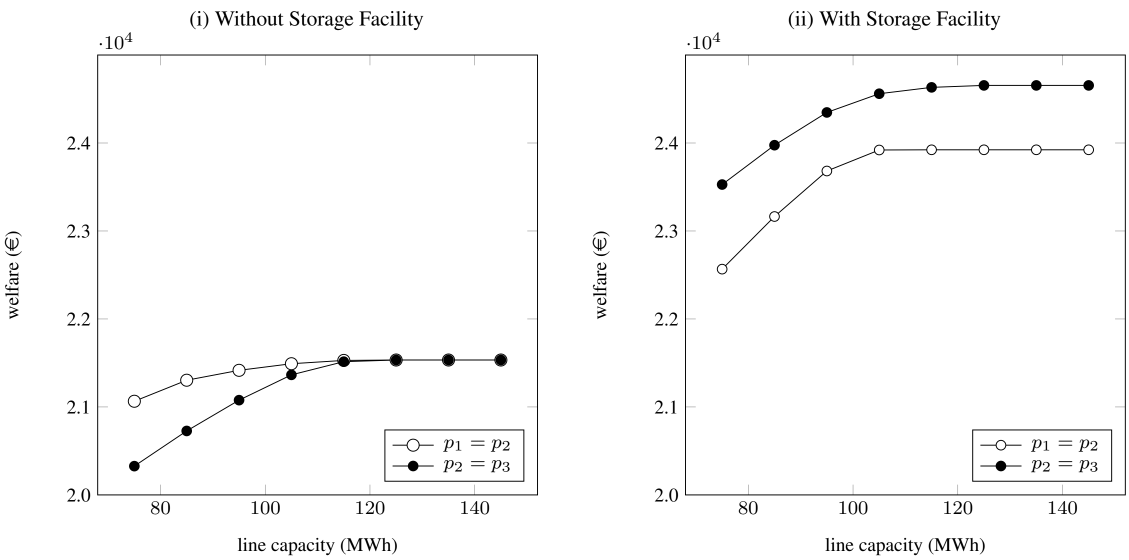

Figure 8: Effects of Different Line Capacities

Similar to Figure 8, we extend the results of our line-capacity analysis to the case of a network with three transmission lines, i.e., a cycle. The new line is characterized by a transmission capacity of 75 MWh. As can

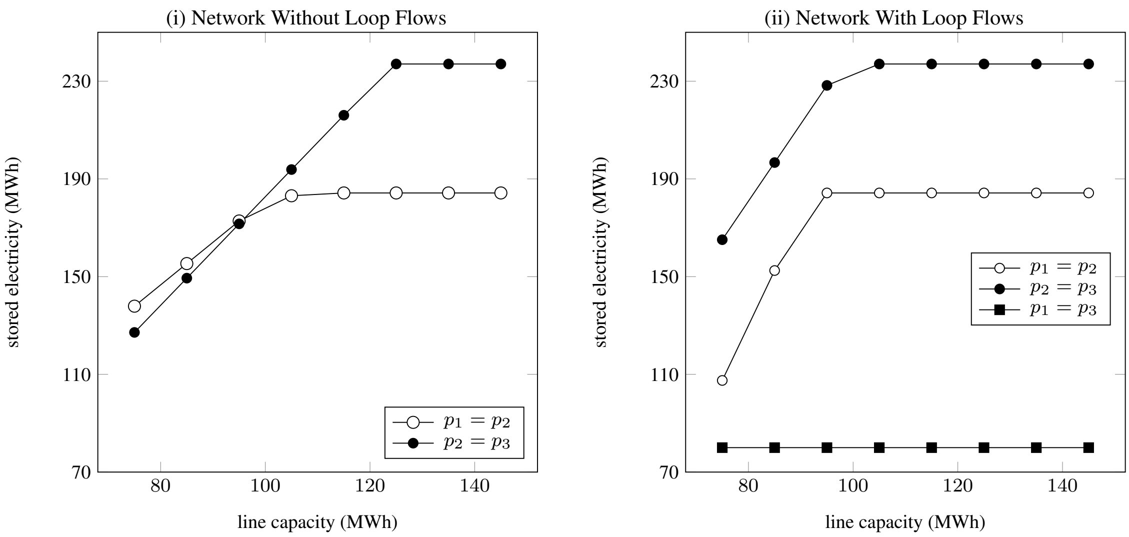

Figure 9: Effects of Different Line Capacities On Stored Electricity

be seen in Figure 10, for a cycle the same results can be identified as for the case of the two transmission lines. In particular, even though a uniform price will be observed in the no-storage case (transmission capacities are large enough to transport all the traded electricity), the introduction of a storage facility yields an inter-regional price divergence, which in turn yields an optimal east-west, two-zone configuration. For policy makers this implies that storage facilities may not only require a reconfiguration of current zonal boundaries, but also yield an update of the optimal number of price zones, which in practice may involve an even more complicated political decision process. We summarize this finding in the following result:

Result 5 (Optimal Number of Price Zones)**.** *The introduction of storage may not only affect the choice of optimal zonal boundaries for a given number of price zones, but also change the optimal number of price zones.*

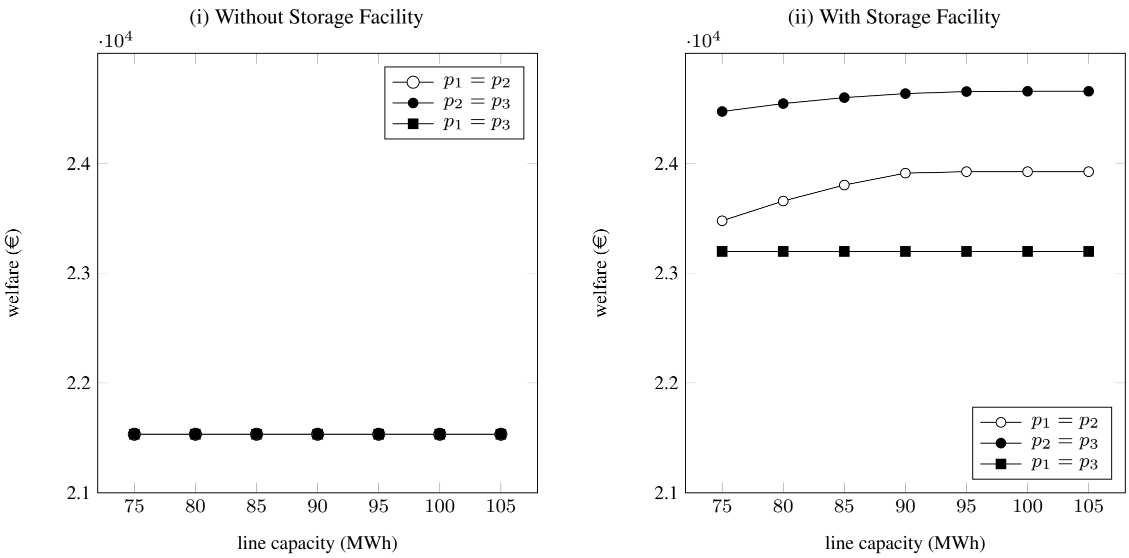

Figure 10: Effects of Different Line Capacities in the Three-Node Network with Loop Flows

5.3. **Storage Facilities and the Variability of (Renewable) Energy Supply.** As discussed in DeCarolis and Keith (2006), Hadjipaschalis et al. (2009), or Beaudin et al. (2010), storage facilities are often seen as a tool for mitigating the variability of renewable energy production. In particular, energy may be stored in periods with an excess production and discharged in periods with a relatively high demand. As highlighted by Strbac et al. (2007), such a volatile generation structure challenges the balancing of demand and supply in the different time periods. To analyze the effects of an intermittent (renewable) energy supply, we modify our example by assuming that the off-peak period is characterized by production functions with decreased cost and larger production capacities as compared to the on-peak period. Thus, period 1 may be interpreted as some kind of a low demand and high wind period, while period 2 may be seen as a high demand and low wind period. For this reason, in Figure 11 we modify the three production functions as compared to the standard functions used in the examples above by different percentage levels that measure some kind of additional wind availability in period 1. As expected, an increasing wind availability yields a higher welfare level in both the storage and no-storage case. Additionally, the inclusion of a storage facility improves the balancing of the varying demand and supply, which is reflected for all wind availability levels in an increased welfare as compared to the no-storage case. Clearly, this underlines the importance of storage facilities that participate at the spot market (and in the corresponding auctioning process) by buying and selling energy in the off-peak and on-peak trading periods, respectively. Turning to the different zonal designs, in the no-storage case again a north-south splitting stays optimal for all considered wind-availability factors, while in the presence of a storage facility the east-west configuration is always the welfare maximizing zonal design.

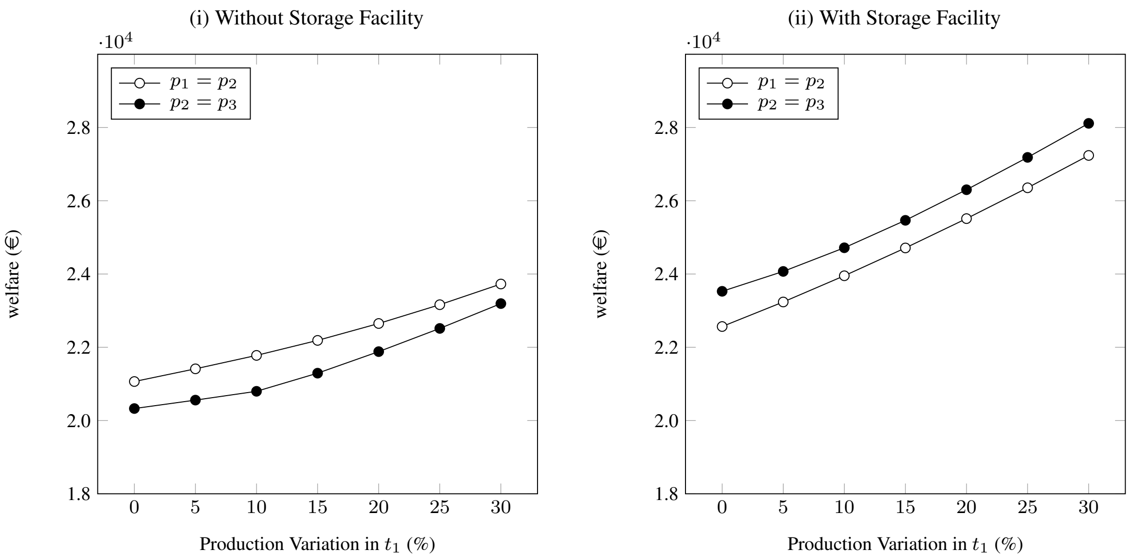

Figure 11: Effects of Variable Supply in the Three-Node Network

The same results are valid also for the three-line, cycle case; see Figure 12. However, for an increased wind availability, the no-storage case is not characterized by a uniform market price in the two periods. Instead, the unique optimal zonal configuration without a storage facility is the north-south splitting (while in the storage-case again an east-west configuration is welfare maximizing). As a main reason, given the increased generation capacities in period 1, transmission capacities are now more restrictive as in the standard case without any additional wind.

5.4. **Different Locations of the Storage Facility.** In this section we analyze the effects of different locations of the storage facility within the network. As can be seen from Table 2, if the storage facility is located in the north, which is described by excess and comparatively cheap supply, the east-west zonal design is the efficient zone configuration. In contrast, if the storage facility is located in the south with a scarce and comparatively expensive supply, the north-south splitting constitutes the welfare maximizing design. However, we note that such an interpretation will not always be possible for general networks with loop flows. Instead, a careful analysis of the chosen zonal configuration must be carried out before implementing a new zonal design. In this context, our model extension described in Section 4.3.3 may be seen as a valuable tool to support such policy decisions.

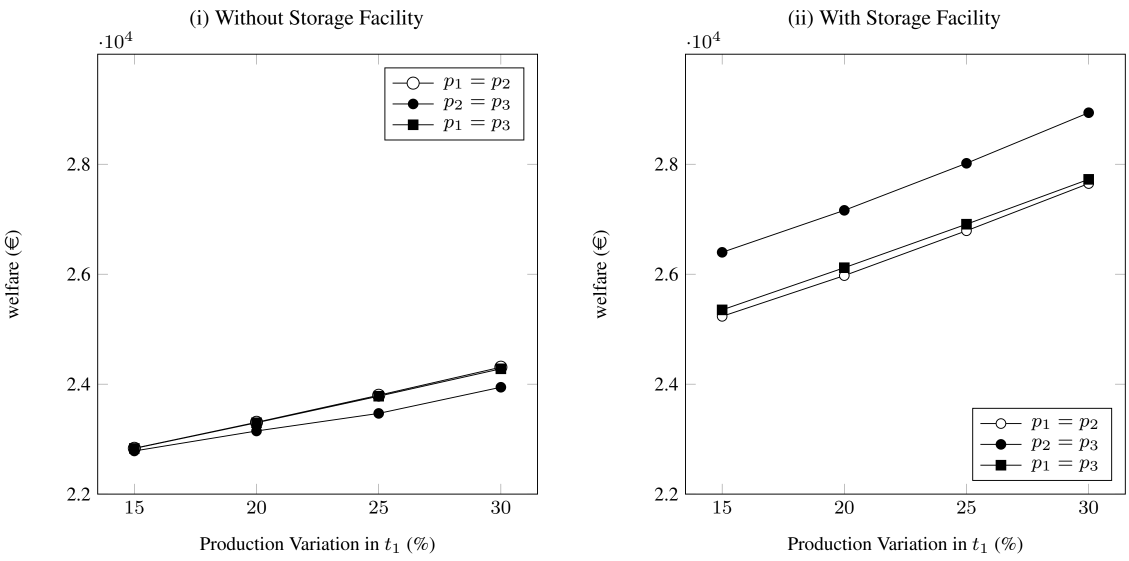

Figure 12: Effects of Variable Supply in the Three-Node Network with Loop Flows

TABLE 2. Locational Effects Of Storage Facilities

Storage	Yes		Yes		Yes		No	
Location Storage Facility	Node 1		Node 2		Node 3		-	
Zone Configuration	North-South	East-West	North-South	East-West	North-South	East-West	North-South	East-West
Welfare	22461.42	23430.83	22566.34	23527.82	22646.87	21268.49	21064.58	20327.08
Demand t_1								
Node 1	0	0	25	25	25	40	25	40
Node 2	80	25.99	105	10	105	10	105	35
Node 3	72.19	65.99	32.1	50	25.12	50	70	75
Demand t_2								
Node 1	68.03	122.21	84.56	104.44	76.8	70.83	33.33	33.33
Node 2	148.03	117.5	164.56	135	156.8	150.83	113.33	113.33
Node 3	126.97	157.5	175	175	196.8	190.83	153.33	153.33
Production t_1								
Node 1	100	100	100	100	100	25	100	50
Node 2	100	100	100	100	100	100	100	100
Node 3	0	0	100	12.16	100	100	0	0
Production t_2								
Node 1	100	100	100	100	100	100	100	100
Node 2	100	100	100	100	100	100	100	100
Node 3	100	100	100	100	100	100	100	100
Stored-in energy in t_1	47.81	108.02	137.9	127.16	144.88	125	-	-
Stored-out energy in t_2	43.03	97.21	124.11	114.44	130.39	112.5	-	-

5.5. **Three-Node Network With Lower Demand Elasticities.** In this section we present the results of our three-node network with lower demand elasticities. In particular, we use linear demand functions with slopes of two in absolute value as depicted in Figure 13. Observe that all storage, transmission, and generation data is identical to the parameters of our standard example in Section 4.

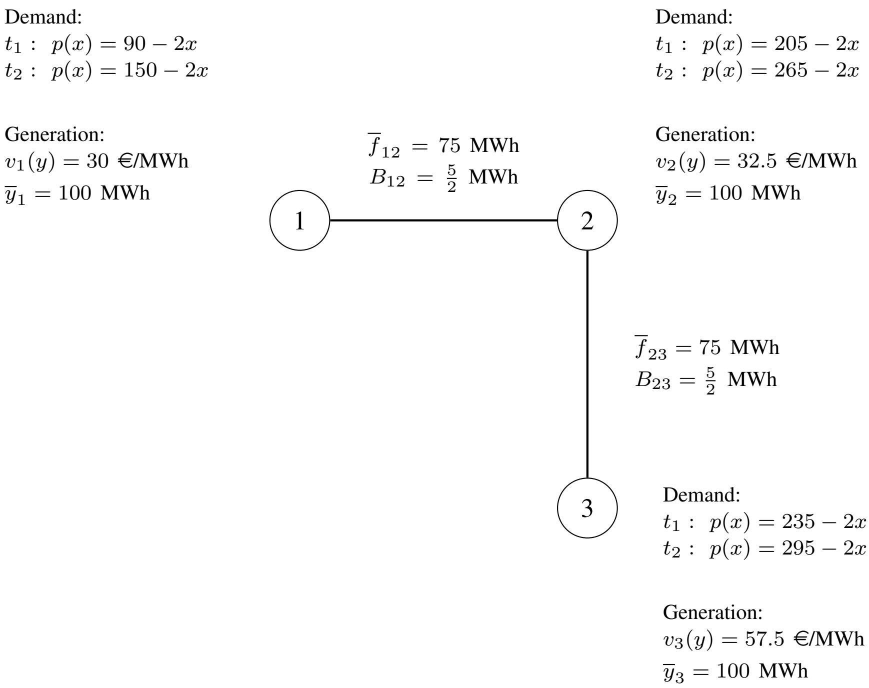

Figure 13: Three-Node Network with Lower Demand Elasticities

As can be seen in Table 3, for the no-storage scenario again the north-south splitting is optimal. In analogy, the east-west zonal design is welfare maximizing in the case of a storage located at node 2. As the demand levels illustrate, the introduction of a storage only yields a low demand reduction in the off-peak period. In addition, in the peak-demand period demand levels are not affected by the inclusion of storage, i.e., demand quantities are identical for the no-storage and for the storage case. In contrast, the production side drives differences between the considered scenarios to a larger degree as compared to the demand side. In particular, using the available storage facility, production in the north is increased in the off-peak period as compared to the no-storage case, while production in the south is decreased in the on-peak period in order to realize savings in terms of reduced production costs.

Observe that in line with our previous results, for both zonal configurations the inclusion of a storage facility yields a welfare increase, i.e., the storage facility is beneficial. Finally, we note that also Result 4 is valid for our modified example with lower demand elasticities. In particular, in the case of a storage facility located at node 2, the resulting nodal pricing solution will be characterized by a three-zone configuration in period 1 and a uniform price system in period 2. In direct consequence, congested transmission lines of the nodal pricing system will fail in determining optimal zonal boundaries in the presence of storage facilities.

To sum up, the observations of this section indicate that our main results and policy conclusions will also hold for the case of lower demand elasticities.

TABLE 3. Solution of the Three-Node Network With Lower Demand Elasticities

Zonal Design	Zonal Pricing			
Zone Configuration	North-South		East-West	
Storage	No	Yes	No	Yes
Welfare	50521.88	50830.63	50310.94	50856.88
Demand in t_1				
Node 1	28.75	25	30	25
Node 2	86.25	82.5	73.75	73.75
Node 3	88.75	88.75	88.75	88.75
Demand in t_2				
Node 1	46.25	46.25	46.25	46.25
Node 2	103.75	103.75	103.75	103.75
Node 3	118.75	118.75	118.75	118.75
Production in t_1				
Node 1	100	100	78.75	100
Node 2	90	100	100	100
Node 3	13.75	13.75	13.75	13.75
Production in t_2				
Node 1	100	100	100	100
Node 2	100	100	100	100
Node 3	68.75	53	68.75	45.12
Stored-in energy in t_1	-	17.5	-	26.25
Stored-out energy in t_2	-	15.75	-	23.63

6. Conclusions and Policy Implications

Even though electricity storage has repeatedly been analyzed in the literature, congestion management studies that deal with zonal pricing traditionally abstracted from price effects of storage facilities; see for instance Bjørndal and Jørnsten (2001), Bjørndal et al. (2003), Ehrenmann and Smeers (2005), Oggioni and Smeers (2013), or Bjørndal et al. (2014). In this paper we are the first to introduce a zonal pricing model with endogenous storage. Our model accounts for consumers, producers, and storage facilities that interact on an electricity network with limited transportation capacities. As we show, storage facilities may not only decrease inter-temporal price variances, but may also increase the inter-regional price differences of an electricity market. These increased inter-regional price variances may change electricity prices in a way that requires a complete reconfiguration of the current zonal boundaries in order to maintain a welfare maximizing zonal design. However, in the short-run market participants may have an incentive to implement a sub-optimal zonal design, which in general causes severe incentive problems. Therefore, we also propose a model variant that determines an optimal zonal configuration when storage facilities are endogenously taken into account. As zonal pricing is implemented in some European countries and in Australia, such endogenous zonal-configuration models may help policy makers to implement welfare maximizing zonal designs in times of increasing storage facility investments. In this context our work also adds to the current process of European bidding-zone review that – despite its growing importance – did not yet raise the issue of storage facilities; compare ACER (2014), ENTSO-E (2014), or ENTSO-E (2015).

To conclude, from an energy-policy perspective, our results clearly indicate that independent of the chosen congestion management system, by selling or buying electricity at the spot market, competitive storage facilities can enhance welfare through a more efficient inter-temporal balancing of demand and supply. In addition, even though competitive storage facilities that participate at the spot market (and in the corresponding auction) will in general yield a welfare increase as compared to the no-storage case, both the current network and market design including the number and configuration of price zones must be chosen in a way that ensure an optimal integration of storage facilities in the electricity system.

Appendix A. Sets, Parameters, and Variables

Tables 4, 5, and 6 summarize the main sets, parameters, and variables used in this paper.

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TABLE 4. Sets

Symbol	Description
$\mathscr{G}$	Electricity network
N	Set of network nodes
L	Set of transmission lines
T	Set of time periods
Z	Set of given price zones
C	Set of relevant zonal configurations
G	Set of generators
$G_n \subset G$	Set of generators located at node n
S	Set of storage facilities
$S_n \subset S$	Set of storage facilities located at node n

TABLE 5. Parameters

Symbol	Description	Unit
$a_{n,t}$	Intercept of price function at node n in period t	€/MWh
b_n	Slope of price function at node n	€/MWh^2
v_g	Variable production cost of generator g	€/MWh
$\overline{y}_g$	Generation capacity of generator g	MWh
ρ_s	Efficiency of storage facility s	%
$\overline{z}_s$	Storage capacity of s	MWh
$\overline{z}_s^+$	Maximum amount of electricity stored at s in one time period	MWh
$\overline{z}_s^-$	Maximum amount of electricity stored out of s in one time period	MWh
$\overline{f}_l$	Transmission capacity of line l	MWh
B_l	Susceptance of line l	MWh
K_l	Normalized line resistance of line l	MWh^{-1}

TABLE 6. Variables and Derived Quantities

Symbol	Description	Unit
$x_{n,t}$	Electricity demand at node n in period t	MWh
$p_{n,t}$	Electricity price at node n in period t	€/MWh
$y_{g,t}$	Electricity generation of g in period t	MWh
$z_{s,t}^+$	Amount of electricity stored at s in period t	MWh
$z_{s,t}^-$	Amount of electricity stored out of s in period t	MWh
$z_{s,t}$	Amount of stored electricity in s at time period t	MWh
$f_{l,t}$	Power flow on line l in period t	MWh
$\Theta_{n,t}$	Phase angle value at node n in period t	rad
σ_c	Decision variable for zonal configuration c	1
$\mathscr{L}_{l,t}$	Loss on line l in period t	MWh

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