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The Impact of Transmission Pricing in Network Industries

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Abstract

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Keywords Transmission Investment, Generation Investment, Market Design, Locational Marginal Pricing, Redispatch, Fluctuating Demand, Scarcity Rents

JEL Classification L94, L51, D41

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The Impact of Transmission Pricing in Network Industries*

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Abstract

The allocation of scarce transmission resources has a considerable impact on investment incentives in network industries. We study the long term effects of two common network management regimes on investment in production and transmission facilities. That is, in one case transmission constraints are directly taken into account through locationally differentiated market prices (simultaneous market clearing). In the other case, a uniform market price is implemented and transmission constraints are resolved in a subsequent congestion market (sequential market clearing). While simultaneous market clearing produces the efficient outcome, sequential market clearing leads to overinvestment in generation and transmission capacity, as we show. These findings contribute to the debate on electricity transmission pricing.

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1 Introduction

When a good is sold through a network, one of the important questions to be answered is whether locationally differentiated prices or a uniform market price should be charged. Locationally differentiated market prices take potential network congestion directly into account. A uniform market price, however, 'enlarges' the market (by ignoring congestion), but makes a mechanism outside the market necessary to alleviate potential congestion. A prominent example for such a problem is given by the management of transmission capacity in liberalized electricity markets. In the U.S., seven regional electricity markets have implemented locational marginal pricing, where prices can differ among locations in the same market and thus, implicitly price transmission constraints directly at the spot market.[1] In contrast, most European electricity markets continue to use redispatch systems, where a single price per market exists and transmission constraints are solved by the system operator after the spot market has taken place. However, intense debates about shifting towards locational marginal pricing are ongoing in the U.K., Germany as well as at the wider European level.[2]

Many contributions have extensively analyzed the impact of different transmission management regimes.[3] However, all these articles typically focus on short run market performance, leaving aside long run aspects such as investment incentives in transmission and generation facilities. Recently, experts as well as policy makers have increasingly emphasized that for the proper functioning of electricity markets not only short run efficiency but also long run incentives are of central importance.[4] Moreover, a detailed analysis of the long run perspective seems to be of particular importance in the light of the ongoing debate on insufficient incentives in liberalized electricity markets to provide generation investment.[5] Till date this debate has entirely abstracted from issues arising due to a transmission network.

This paper sheds light on the relationship between transmission management and long term investment in generation and transmission capacity. Thus, we develop a network model with endogenous generation and transmission capacities. Competitive firms invest in two different generation technologies, which allows production at different levels of demand. Transmission investment is assumed to be optimal, anticipating subsequent generation investment. The capacity of the transmission line limits the amount of physical trade that can take place. As transmission constraints

[1]For a description of the regional electricity markets in the U.S. compare, e.g., http://www.ferc.gov/.

[2]Compare, e.g., Ofgem (2010) and Redpoint Energy (2011) for the British discussion, Frontier (2011) for the discussion in Germany and European Parliament (2009), European Council (2011), Acer (2011) and Electricity Regulatory Forum (2011) for efforts on the European level.

[3]Compare Joskow and Tirole (2000) and Gilbert, Neuhoff and Newbery (2004) who analyze the effect of different transmission allocation mechanisms on generation spot market conduct and Green (2007) who estimates the short run welfare loss due to sequential market clearing compared to simultaneous market clearing.

[4]Compare, e.g., Baldick, Bushnell, Hobbs and Wolak (2011) for an expert opinion and European Parliament (2009) for a policy viewpoint.

[5]See, e.g., Oren(2005), Hogan (2005), Cramton and Stoft (2006), Joskow (2007) or Cramton and Ockenfels (2011) on the 'missing money discussion'.

might potentially exist in this network, a mechanism for transmission allocation is needed. We investigate two different, frequently applied mechanisms for transmission allocation: *Simultaneous market clearing* and *sequential market clearing*. Our benchmark case is given by *simultaneous market clearing* ('locational marginal pricing'), where separate spot market prices exist at the different nodes in the network. Whenever the level of demand and hence, the amount of trade is high, such that a transmission line is constrained, the spot market prices depart from each other. This leads to an efficient allocation and the spot market is directly cleared. With *sequential market clearing* ('redispatch system'), a single spot market price exists in the whole network. Whenever the level of demand is high, such that the transmission line is constrained, the spot market outcome becomes physically infeasible. In order to achieve market clearing, an adjustment market has to be run, where the system operator engages in counter-trading. That is, the system operator acts as a seller at the exporting side of the constrained line and as a buyer at the importing side of the constrained line. These additional transactions reduce the level of trade between the two nodes to a physically feasible level.[6]

First, our benchmark case with simultaneous market clearing produces the socially optimal investment outcome.[7] Simultaneous market clearing ensures that generation is priced at its locational marginal value. This gives competitive firms the efficient price signals for generation investment and hence, given the optimal generation capacity, transmission investment is also conducted efficiently.

Second, sequential market clearing, on the other hand, leads to overinvestment in total generation and transmission capacity. Sequential market clearing disentangles the price signal from the location of production and hence, from its locational marginal value. This leads to higher generation scarcity rents and therefore, to exaggerated investment incentives in generation. As we show, the transmission capacity matches the generation capacity. Thus, there is also overinvestment in the corresponding transmission line.

Finally, we find that with simultaneous market clearing the socially optimal technology mix is reached. In contrast, with sequential market clearing the technology mix is distorted towards more peakload and less baseload generation capacity.

The central message of our findings is that policy makers should be aware that switching from a system of sequential market clearing to a system of simultaneous market clearing leads to a reduction of investment incentives. In a setting like ours, that is, without any market distortions, this is desirable as it leads to the socially optimal investment outcome. However, if investment incentives in a specific market are already perceived as too low, a change of the transmission man-

[6]The expressions counter-trading and (market-based) redispatch are used interchangeably in this article. Both expressions describe methods to alleviate transmission congestion outside the spot market. Under both methods, the system operator makes market transactions against the 'direction' of trade at the spot market in order to reduce the traded quantity over the transmission line until the congestion is eliminated.

[7]This result is in line with the previous literature on locational marginal pricing (see Hogan, 1999).

agement regime might then further aggravate these problems. Inadequate investment incentives might be a result of market imperfections and institutional constraints in electricity markets, such as price caps, which suppress electricity prices below the efficient level. Hence, generation revenues might be insufficient to provide adequate generation capacity (compare the 'missing money discussion', e.g., Oren, 2005, Hogan, 2005, Cramton and Stoft, 2006, Joskow, 2007, and Cramton and Ockenfels, 2011). Policy makers should then be aware of the potentially increased necessity to adopt appropriate measures to enhance firms' investment activities. However, in this paper we abstract from any of these market imperfections. Notice that our results should not be understood as a justification for the introduction or the retention of sequential market clearing as a proper mechanism to enhance firms' investment activity in a specific electricity market.

This work is related to the literature on the regulation of electricity transmission. Bushnell (1999), Joskow and Tirole (2000), and Gilbert, Neuhoff and Newbery (2004) analyze different transmission capacity allocation methods and how these affect the spot market outcomes in markets with simultaneous market clearing. Wolak (2011) measures the benefits from introducing simultaneous market clearing in the Californian electricity market and Green (2007) calculates the welfare loss associated with sequential market clearing relative to simultaneous market clearing in England and Wales. However, these articles do not take any long term aspects like investment in generation or transmission capacities into account. Another strand in the literature explicitly considers the impact of different regulatory measures on transmission investment. Léautier (2000), Vogelsang (2001), Bushnell and Stoft (1997), Hogan (1992), Joskow and Tirole (2005), Sauma and Oren (2009), and Hogan, Rosellón and Vogelsang (2010) analyze different regulatory instruments to incentivize transmission investment. As compared to our work, however, these articles do not consider the impact of different transmission management systems. Moreover, we also analyze a potential change in the generation stock.[8] To the best of our knowledge, this article is the first one to derive the impact of the transmission management system on investment incentives in generation and transmission facilities.

Last but not least, this article is related to the peak load pricing literature, that has investigated generation investment incentives under fluctuating and potentially uncertain demand and emphasized the effect of the spot market design. A good overview of the literature is provided by Crew, Fernando and Kleindorfer (1995). Boom (2009) and Fabra, von der Fehr and de Frutos (2011) analyze the effect of auctions at the spot market. Reynolds and Wilson (2000) and Fabra and de Frutos (2011) analyze the case of Bertrand spot markets. Gabszewicz and Poddar (1997), Murphy and Smeers (2005), and Zöttl (2011) analyze strategic investment prior to Cournot competition. All these contributions completely abstract from the problems implied by the presence

[8]Our work explicitely considers investment in transmission and generation. Sauma and Oren (2006) show in their paper that analyzing transmission investment, taking the generation capacity in the market as given, leads to significantly distorted predictions. Rious, Glachant and Dessante (2010) extend the analysis by Sauma and Oren by assuming that anticipation is costly.

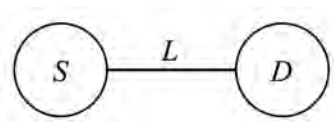
of a transmission network.

In the next Section we present our model. In Section 3 we analyze simultaneous market clearing. In Section 4 we analyze sequential market clearing and compare the results. In Section 5 we relate our work to the current discussion on transmission management in the electricity sector. In Section 6 we discuss an extension and generalize our results in a n-node network. In Section 7 we put forward some concluding remarks.

2 The Model

We consider a network as described in Figure 1 where consumption takes place at a 'demand node', denoted by D, and production takes place at a 'supply node', denoted by S. Both nodes are connected via a transmission line. Trade between consumers at the demand node and producers at the supply node is limited by the transmission line's capacity L.

Figure 1: Two-node network



Competitive firms at the supply node can invest in production capacity. This allows these firms to produce at a spot market with variable levels of demand at the demand node. Production takes place given the constraints by transmission and generation capacities. Inverse demand is given by the function $P(Q, \theta)$, which depends on output $Q \in \mathbb{R}^+$ with $P_Q(.) < 0$, and the variable $\theta \in \mathbb{R}$ which captures the different levels of demand. The frequencies of all different levels of demand are denoted by $f(\theta)$, their support is given by $[\underline{\theta}, \overline{\theta}]$ and their cumulative distribution is denoted by $F(\theta)$.[9] We normalize $F(\theta)$ such that $F(\underline{\theta}) = 0$ and $F(\overline{\theta}) = 1$. Throughout the article we will refer to the different levels θ of spot market demand simply as to 'spot market θ'.[10] The firms are assumed to be price takers and the spot market is perfectly competitive.

We analyze the case of two different production technologies, which are available at the supply node, a 'baseload' production technology and a 'peakload' production technology. The baseload

[9] θ can be interpreted as a parameter representing the electricity demand in a particular hour. Accordingly, $F(\theta)$ can be interpreted as the probability distribution over all demand realization within the 8760 hours in a year.

[10] Notice that at the time of investment firms do not necessarily need to know the demand levels at all spot markets. In order to keep notation to a minimum, we do not explicitly disentangle demand fluctuations occurring at spot markets in several periods from uncertainty regarding the precise pattern of those fluctuations. Notice, however, that the parameter $\theta \epsilon [\underline{\theta}, \overline{\theta}]$ of our model is suited to capture both phenomena.
The demand fluctuations are central to our analysis, as only then the different market clearing mechanisms begin to matter. An analysis without demand fluctuations would thus not generate any useful insights for the design of liberalized electricity markets. We discuss the implications stemming from the demand fluctuations in detail in section 4.

(peakload) technology comes with production cost c_1 (c) and the cost of capacity investment is given by k_1 (k), with $c_1 < c$ and $k_1 > k$.[11] We denote the equilibrium industry investment by (X, X_1), where X represents total investment and X_1 represents baseload investment. Peakload investment is given by the difference of total and baseload investment $(X - X_1)$.

Investment in the transmission line investment is taking place optimally, given subsequent generation investment. A natural as well as realistic interpretation of this assumption would be that transmission line investment is determined by a welfare maximizing regulator. The transmission line is assumed to be operated by a (independent) system operator. The nominal line size is denoted by L and the marginal cost of investment in the transmission line by t. For the main part of this paper we assume that investment in additional transmission capacity is less costly than investment in peakload capacity, that is, $t < k$. This reflects the situation in the electricity sector, where transmission expansion is considerably cheaper than generation expansion.[12] In section 6 we relax this assumption in order to discuss its relevance for our results. Generators know their production capacities, the nominal line capacity as well as the spot market demand at the time of making their production decision. Hence, produced quantities are contingent on the demand scenarios $\theta \in [\underline{\theta}, \overline{\theta}]$. However, the exact transmission capacity is only known after spot market production decisions have been made. This assumption is needed in order to establish an equilibrium. We abstract from any cost of transmission operation like line losses or other system services.

We consider two different mechanisms for transmission management in this paper. Under *simultaneous market clearing* the operation of the network is governed by a system of optimal nodal prices, that is, a price at the supply node and a price at the demand node. These nodal prices adjust in such a way that the market is always cleared. If transmission capacity is abundant, trade between the two nodes leads to identical prices at both nodes. However, if transmission capacity is scarce, trade between the two nodes is restricted and prices at the two nodes depart. At the demand node a high price occurs, while at the supply node competition among generators leads to a low price. The price differences between the two nodes in the case of a congested transmission line ('congestion rents') can be used by the regulator to finance transmission investment.

Under *sequential market clearing* the operation of the network is governed by a single spot market price in the whole network. In case the transmission capacity is scarce, trade at the spot market takes place as if no congestion occurs, though this might lead to physically infeasible spot market outcomes. After the spot market has taken place and the de facto transmission capacities are

[11] In the case of the electricity sector, nuclear-, lignite-, coal-, and gas-fired power plants are usually used by energy companies. Nuclear power plants have very high investment costs but a low cost of production, while gas-fired power plants have relatively low investment cost and a high cost of reduction. Hence, nuclear power plants can be interpreted as baseload plants and gas-fired power plants as peakload plants. Lignite- and coal-fired power plants have a cost structure that locates them somewhere in between nuclear- and gas-fired plants. Notice that if a technology with low (high) production and low (high) investment costs would be available, a corner solution would arise, where this technology would be the only technology in the market or it would not be used at all.

[12] An overview of investment costs for different generation and transmission technologies can be found in Schaber, Steinke and Hamacher (2012).

realized, the system operator assures whether or not the spot market outcome is feasible, that is, production is not larger than transmission capacity. If this is not the case, the system operator runs an adjustment market. In this market the system operator engages as a seller at the demand node and as a buyer at the supply node, such that the production volume just matches the transmission capacity. Notice that in the adjustment market the price at the demand node always lies above the price at the supply node. Hence, it is costly for the system operator to run the adjustment market. The adjustment market as well as transmission investment are financed via a transmission fee raised from the generators.

The timing is as follows: 1.) The optimal transmission investment decision is made. 2.) Generators decide upon generation capacity investments. 3.) The system operator runs the spot market: (*i*) Spot market realization θ is determined. (*ii*) Generators set production quantities. (*iii*) Transmission line uncertainty is revealed. (*iv*) If necessary, in a system with sequential market clearing, the system operator runs the adjustment market.

3 Simultaneous Market Clearing

In this section, we analyze the effect of a spot market design with simultaneous market clearing on industry investment in generation capacity and the optimal transmission capacity investment. With simultaneous market clearing, spot market prices at the two nodes in the network depart from each other when the transmission line is constrained. This system allows to directly take transmission constraints into account at the spot market.

In order to understand the concept of simultaneous market clearing, we provide a short description of the spot market: For given generation and transmission capacities, competitive generators want to produce until marginal cost equals the market price. The marginal cost is either given by the characteristics of the baseload or the peakload production units. Moreover, generators are constrained by their capacity in their production decision. The latter is denoted by $Q'(\theta)$. Demand is restricted by the transmission capacity L, which is needed to transport the electricity from the supply to the demand node. As long as the transmission capacity exceeds the generation production decision ($Q'(\theta) < L$) trade takes place without limitations. However, if the generation production decision exceeds the transmission capacity ($Q'(\theta) > L$) the price at the demand node rises above the price at the supply node, which is kept down at marginal cost through competition among generators.

In order to be able to establish an equilibrium under simultaneous market clearing a small technical assumption has to be made. When the production decision equals the transmission capacity ($Q'(\theta) = L$) an arbitrarily small amount of uncertainty for the overall size of transmission is needed. The transmission line is subject to some uncertainty, that is, the de facto transmission capacity, denoted by T, is slightly different from the nominal line size and given by $T = L + \varepsilon$.[13] The support $[-\epsilon, +\epsilon]$ of the random shock ε can be deliberately small (i.e., $\epsilon \to 0$). We denote the density of T by $g(T)$ and its distribution by $G(T)$. For simplicity, if $|L - Q'(\theta)| < \varepsilon$ holds, we refer to $Q'(\theta) = L$ in the remainder of this paper. This implies that peakload generation units can only earn positive scarcity rents, if the de facto line capacity exceeds the total generation capacity $(T \geq X)$.

The following lemma characterizes investment under a system with simultaneous market clearing.

Lemma 1 *[Generation and Transmission Investment - Simultaneous Market Clearing] Under a system with simultaneous market clearing, industry investment in generation* $\left(\hat{X}, \hat{X}_1\right)$ *is uniquely characterized by*

$$\hat{X}: \left\{\left(1 - G\left(\hat{X} - \hat{L}\right)\right) \int_{\theta^X}^{\bar{\theta}} \left(P\left(\hat{X}, \theta\right) - c\right) dF(\theta) = k\right\}$$

$$\hat{X}_1: \left\{\int_{\theta^{\underline{X_1}}}^{\theta^{\overline{X_1}}} \left(P\left(\hat{X}_1, \theta\right) - c_1\right) dF(\theta) + \int_{\theta^{\overline{X_1}}}^{\bar{\theta}} (c - c_1)\, dF(\theta) = k_1 - k\right\}$$

The optimal line $\left(\hat{L} = \hat{X}\right)$*, given industry investment, is uniquely characterized by*

$$\hat{L}: \left\{G\left(\hat{X} - \hat{L}\right) \int_{\theta^X}^{\bar{\theta}} \left(P\left(\hat{L}, \theta\right) - c\right) dF(\theta) = t\right\}.$$

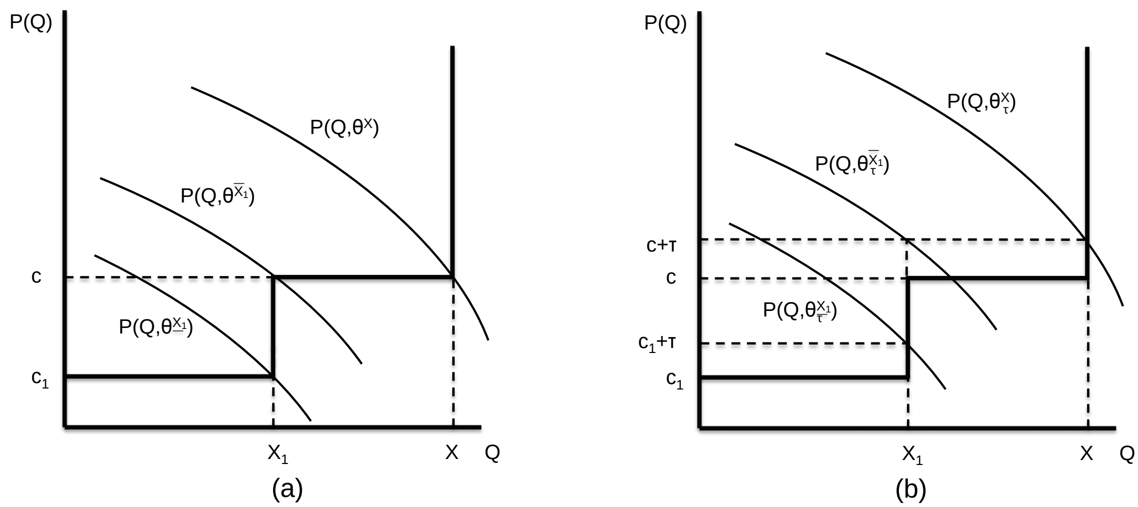
$\theta^{\underline{X_1}}$ *is the spot market scenario beyond which baseload investment is binding,* $\theta^{\overline{X_1}}$ *is the spot market scenario beyond which firms produce at the marginal cost of the peak load technology* c *and* θ^X *is the spot market scenario beyond which total investment is binding.*

Proof. See Appendix. ■

The critical spot market scenarios are illustrated in graph (a) of Figure 2. Notice that $\theta^{\underline{X_1}}$, $\theta^{\overline{X_1}}$ and θ^X are defined by the respective spot market conditions, that is: At $\theta^{\underline{X_1}}$ and quantity X_1 marginal revenue equals the marginal cost of baseload production c_1. At $\theta^{\overline{X_1}}$ and quantity X_1 marginal revenue equals the marginal cost of peakload production c. At θ^X and quantity X marginal revenue is equal to the marginal cost of peakload production c.

[13]Notice that this assumption is in line with the technical properties of electricity transmission. De facto transmission capacities usually depend on environmental conditions and operational actions in the transmission network. For example, 'the import capacity of Path 15 (connecting Northern and Southern California) varies between about 2600 MW and 3950 MW depending upon the ambient temperature and remedial action schemes that are in place to respond to unanticipated outages of generating plants and transmission lines.' (see Joskow and Tirole (2005), fn. 20)

Figure 2: Illustration of the critical spot market scenarios for given investment decisions (X, X_1, L), with $X = L$. (a) critical spot market scenarios in the absence of a transmission fee τ. (b) critical spot market scenarios when a transmission fee τ exists.



The characterization of the investment outcome in the lemma is rather intuitive.

First, generation and transmission capacity are of equal size $\left(\hat{X} = \hat{L}\right)$: The optimal transmission line capacity does not exceed the generation capacity built by investors $\left(\hat{L} \leq \hat{X}\right)$ as capacity is costly and the exceeding capacity would never be utilized. In addition, peakload generators can only earn positive scarcity rents at the spot market, when they constitute the constraining element in the market $\left(\hat{X} \leq \hat{T}\right)$. Hence, generation capacity does not exceed the transmission capacity $\left(\hat{X} \leq \hat{L}\right)$. As neither generation nor transmission capacity is larger than the other in equilibrium, it has to hold that both are of equal size $\left(\hat{X} = \hat{L}\right)$.

Second, consider total generation capacity. In equilibrium, the scarcity rents earned by generators beyond spot market θ^X, when the transmission line is not congested, are equal to the marginal cost of investment k. As the nominal transmission capacity $\hat{L}$ differs from the de facto transmission capacity, that is, $\hat{T} = \hat{L} + \varepsilon$, the transmission line is uncongested with probability $1 - G\left(\hat{X} - \hat{L}\right)$. Notice that investment in generation capacity is solely determined by the peakload generation characteristics. Due to the higher production cost, the peakload generation units are employed in the spot market only after baseload generation units have been fully utilized, that is, beyond demand realization $\theta^{\overline{X_1}}$. Hence, the characteristics of these 'marginally' employed generation units are decisive for total capacity investment. Additional capacity is only valuable at the marginal demand levels, when capacity is scarce, that is, beyond demand realization θ^X, when total capacity is met and the spot market price rises above the peakload production cost c.

Third, consider transmission capacity. In equilibrium, the marginal value of transmission capacity, namely, the scarcity rents when the transmission line is congested beyond spot market θ^X, is equal to the marginal cost of investment t. Congestion only occurs beyond spot market θ^X with probability $G\left(\hat{X}-\hat{L}\right)$. Notice that the price differences occurring between the supply and the demand node just equal the transmission investment costs. Hence, no additional revenue for financing the transmission line is necessary and no extra transmission fee is needed. The identical result can also arise as the outcome in a transmission merchant investment model, where financial transmission rights are issued to investors to determine and finance the transmission capacity (see also Joskow and Tirole (2005)).

Fourth, the most intuitive way to describe baseload capacity investment $\hat{X}_1$ is as a replacement trade-off. Replacing a unit of baseload generation with a unit of peakload generation causes higher investment costs by $k_1 - k$ as the former is more expensive to build than the latter. However, the baseload unit has cheaper production costs. Therefore, at all spot markets when peakload generation is used, that is, beyond $\theta^{\overline{X_1}}$, substituting peakload with baseload generation creates a gain equal to the difference in production cost $c - c_1$. Moreover, the baseload unit is already profitable to run at lower spot markets as the peakload unit, that is, before $\theta^{\overline{X_1}}$, and earns additional scarcity rents whenever baseload capacity is constrained but peakload generation is not profitable to run yet, that is, at all spot markets $\theta\epsilon\left[\theta^{\underline{X_1}}, \theta^{\overline{X_1}}\right]$.

The following remark compares the investment performance under simultaneous market clearing with the socially optimal investment outcome which is denoted by (X^*, X_1^*, L^*).

Remark 1 *[Generation and Transmission Investment - Simultaneous Market Clearing] The solution obtained under a system with simultaneous market clearing gives rise to the socially optimal investment, in total generation investment* $\left(\hat{X}=X^*\right)$*, in the baseload technology* $\left(\hat{X}_1=X_1^*\right)$ *as well as in the transmission line* $\left(\hat{L}=L^*\right)$.

Proof. See Appendix. ■

This result is in line with the previous literature on locational marginal pricing (see, e.g., Hogan (1999) or Joskow and Tirole (2005)). Since generation investors behave perfectly competitive, firms invest in additional generation capacity up to the point when the generation scarcity rents equal the investment cost and the marginal profit from investment is zero. With simultaneous market clearing, these scarcity rents at each spot market realization just reflect the locational marginal value of generation at each node and provide the efficient signal for investment. Hence, the generation investment outcome corresponds to the socially optimal solution.

4 Sequential Market Clearing

This section analyzes industry investment in generation capacity and optimal investment in transmission capacity under sequential market clearing. Subsequently, we compare the outcome to the results from section 3. With sequential market clearing only a single spot market price for the whole network exists. This single spot market price is insufficient to take transmission constraints into account and might lead to infeasible spot market outcomes. Therefore, if necessary, the system operator runs an adjustment market to finally achieve market clearing after the spot market has taken place and when the actual transmission capacity is known.

In order to understand the concept of sequential market clearing, we provide a short description of the spot market: For given capacities, competitive generators want to produce until marginal cost equals the market price. The marginal cost is either given by the characteristics of the baseload or the peakload production units. The resulting spot market production decision, denoted by $Q'(\theta)$, is constrained by the generators capacity. Moreover, trade is physically restricted by the de facto transmission capacity T. However, with sequential market clearing, trade at the spot market takes place as if this transmission constraint did not exist. That is, the generators' production decision at the spot market might even exceed the transmission capacity ($Q'(\theta) > T$). Yet, such a spot market outcome is physically infeasible. In order to ensure market clearing in this case, the system operator runs an adjustment market after the spot market has taken place. At the adjustment market, the system operator engages as a buyer of the 'exceeding' quantity $Q'(\theta) - T$ at the demand node and as a seller of equal quantity at the supply node, such that the market outcome becomes feasible. This produces prices at the adjustment market, which are equal to the spot market prices at the different nodes with simultaneous market clearing, though the trade volume at the adjustment market is less. Notice that in contrast to simultaneous market clearing, where revenues are generated through the price differences, running a market with sequential market clearing is costly. The reason is that the system operator has to engage as a buyer at the 'expensive' demand node and as a seller at the 'inexpensive' supply node.

The following lemma characterizes investment in generation and transmission under a system with sequential market clearing.

Lemma 2 *[Generation and Transmission Investment - Sequential Market Clearing] Under a system with sequential market clearing, industry investment in generation* $\left(\tilde{X}, \tilde{X}_1\right)$ *is uniquely characterized by*

$$\tilde{X}: \left\{ \int_{\theta_\tau^X}^{\bar{\theta}} \left(P\left(\tilde{X}, \theta\right) - \tau - c \right) dF(\theta) = k \right\}$$

$$\tilde{X}_1: \left\{ \int_{\theta_{\underline{\tau}}^{X_1}}^{\theta_\tau^{\overline{X_1}}} \left(P\left(\tilde{X}_1, \theta\right) - \tau - c_1 \right) dF(\theta) + \int_{\theta_\tau^{\overline{X_1}}}^{\bar{\theta}} (c - c_1)\, dF(\theta) = k_1 - k \right\}.$$

The optimal line $\left(\tilde{L}=\tilde{X}\right)$, *given industry investment, is uniquely characterized by*

$$\tilde{L}:\left\{\int_{\theta_{\tau}^{L}}^{\bar{\theta}}\left(P\left(\tilde{L},\theta\right)-c\right)dF\left(\theta\right)\geq t\right\}.$$

τ *is a transmission fee the regulator charges in order to compensate the transmission investment expenses.* $\theta_{\tau}^{\underline{X_1}}$ *is the spot market scenario beyond which baseload investment is binding,* $\theta_{\tau}^{\overline{X_1}}$ *is the spot market scenario beyond which firms produce at the marginal cost of the peak load technology* c, θ_{τ}^{X} *is the spot market scenario beyond which total investment is binding and* θ_{τ}^{L} *is the spot market scenario beyond which the transmission capacity is binding.*

Proof. See Appendix. ■

The critical spot market scenarios are illustrated in graph (b) of Figure 2. $\theta_{\tau}^{\underline{X_1}}$, $\theta_{\tau}^{\overline{X_1}}$, θ_{τ}^{X} and θ_{τ}^{L} are defined by the respective spot market conditions, that is: At $\theta_{\tau}^{\underline{X_1}}$ and quantity X_1 marginal revenue is equal to the marginal cost of baseload production plus the transmission fee, $c_1+\tau$. At $\theta_{\tau}^{\overline{X_1}}$ and quantity X_1 marginal revenue is equal to the marginal cost of peakload production plus the transmission fee, $c+\tau$. At θ_{τ}^{X} and quantity X marginal revenue is equal to the marginal cost of peakload production c plus the transmission fee, $c+\tau$. Again, the characterization of the investment outcome in the lemma is rather intuitive. We discuss the investment outcome in detail in the following paragraphs.

First, generation capacity is built as if transmission constraints did not exist. In equilibrium the total generation scarcity rents, that is, beyond spot market realization θ_{τ}^{X}, are equal to the peakload generation investment cost k, regardless of potential transmission congestion. However, notice that the generation scarcity rents are reduced by the transmission fee τ. As the transmission fee increases the generators' perceived production cost above the actual production cost, the generators produce less quantity at all spot markets when capacity constraints are not met and capacity constraints are only reached at higher spot markets. That is, generators earn scarcity rents only at spot markets beyond θ_{τ}^{X}. An illustration of these distortions can be found in graph (b) of Figure 2.

Second, consider transmission capacity. In equilibrium, the marginal value of transmission capacity is equal to the marginal cost of investment t. Notice that, as generation investment takes place regardless of the existence of sufficient transmission capacity, the marginal value of transmission capacity is equal to the full scarcity rents beyond spot market θ_{τ}^{L} for $\tilde{L}\leq\tilde{X}$. Furthermore, since $t<k$, the marginal value of transmission capacity is larger than the marginal revenue of generation capacity. Hence, the optimal transmission capacity is never smaller than the generation capacity. As the optimal transmission capacity also never exceeds the generation capacity, the transmission capacity again just matches the generation capacity $\left(\tilde{L}=\tilde{X}\right)$. Finally, observe that since $\tilde{L}=\tilde{X}$ there is no trading volume at the adjustment market and no extra cost for running the adjustment

market occurs.

Third, the baseload generation investment outcome can again be best understood in a replacement context as in Section 3, under simultaneous market clearing. Replacing a peakload by a baseload generation unit causes higher investment costs. However, it also decreases the production cost, whenever it is profitable for a peakload unit to produce. Moreover, production becomes profitable at spot market realizations, when peakload units would still be unprofitable to run.

Now we can state our main result, which compares investment under sequential market clearing with investment under simultaneous market clearing.

Proposition 1 *[Generation and Transmission Investment] If demand is inelastic,* $\mid \eta \mid \leq 1$*, the solution obtained under a system with sequential market clearing gives rise to*

(i) *higher investment in total generation capacity* $\left(\tilde{X} > \hat{X}\right)$,

(ii) *lower investment in baseload capacity* $\left(\tilde{X}_1 < \hat{X}_1\right)$ *and*

(iii) *higher investment in total transmission capacity* $\left(\tilde{L} > \hat{L}\right)$

compared to investment under a system with simultaneous market clearing.

Proof. See Appendix. ■

Let us provide an intuition for this result. Regardless of the specific market design, the cost of transmission investment has to be fully recouped from the market participants. Under simultaneous market clearing, the transmission congestion rents are sufficient for financing the transmission line. These price differences only occur at the 'marginal' spot markets, that is, beyond θ^X, when generators potentially earn scarcity rents which determine the generation capacity. Under sequential market clearing, no such price differences occur. A linear transmission fee is levied on the generators' usage of the transmission line at all spot market realizations. This implies that the cost of transmission investment is partly recouped at the 'inframarginal' spot market realizations, that is, before θ^X_τ, which are irrelevant for the investment decision. Therefore, the transmission fee is lower than it would be if it was only collected at the marginal spot market realizations. Thus, the transmission fee is also lower at all spot market realizations beyond θ^X_τ, and consequently, the scarcity rents earned by generators' are larger compared to a system with simultaneous market clearing. With larger scarcity rents, investment becomes more profitable and more generation capacity is built.

However, notice that the spot market distortions caused through the transmission fee have the reverse effect on investment. Hence, the result in Proposition 1 only holds if demand is inelastic

($|\eta| \leq 1$). Most studies find price elasticities of demand in the electricity sector of $0.1 - 0.5$ in the short run and $0.3 - 0.7$ in the long run. See, e.g., Lijsen (2006) for an overview of recent contributions on that issue. This implies that the introduction of the transmission fee does not cause too severe spot market distortions. That is, the spot market quantities are not distorted too much, and hence, the critical spot market realizations are not too different from those without a transmission fee.

The result for baseload investment is contrary to that for total investment. Under simultaneous market clearing, firms' replacement decisions are independent of the level of transmission capacity (as long as we have an interior solution with positive peakload investment). Hence, the replacement decision is independent of the cost of the transmission line. In principle, this also obtains under sequential market clearing, that is, the transmission fee τ has no impact on the replacement decision. An exception is given, however, by those spot market realizations, where baseload is binding, as scarcity rents in those cases are reduced. In total, this leads to lower baseload investment compared to simultaneous market clearing. Eventually, as the transmission capacity just matches the generation capacity, the transmission capacity is also larger compared to simultaneous market clearing.

Finally, it is noteworthy that the assumption on fluctuating demand is central for our results. Only then the different market clearing mechanisms begin to matter. As explained in this section, investment differs between sequential and simultaneous market clearing, as the generation scarcity rents are different. This is due to the fact that under sequential market clearing the cost of transmission investment is partly recouped at the 'inframarginal' spot market realizations before θ_τ^X. Hence, the transmission fee is lower at all spot market realizations beyond θ_τ^X, and consequently, the scarcity rents earned by generators are larger compared to a system with simultaneous market clearing. Without demand fluctuations, this distinction could not be made, as only a single spot market realization exists. An analysis without demand fluctuations would thus not generate any useful insight on the impact of different transmission management regimes on firms' investment incentives as analyzed in the present framework.

5 Policy Implications

The allocation of scarce transmission capacity in electricity markets is an intensely debated topic. In the U.S., seven regional electricity markets have introduced simultaneous market clearing: The PJM electricity market in 1998, the New York (NYISO) market in 1999, the New England market (ISO-NE) in 2003, the Midwest market (MISO) in 2005, the California market (CAISO) and the Southwest Power Pool (SPP) in 2007 and the Texas market (ERCOT) in 2010.[14] In contrast,

[14] Compare also, e.g., O'Neill et al., (2006), (2008).

most European electricity markets continue to use sequential market clearing. To this date, simultaneous market clearing has only been introduced in the Polish electricity market in 2011. However, the rapid and regionally concentrated increase in new and low-carbon generation as well as the retirement of old generation in Europe puts pressure on the existing transmission grid. This creates the need for efficient transmission management.[15] This development has led to intense debates about shifting towards simultaneous market clearing in the U.K. as well as in Germany. The British electricity regulator *Ofgem* is currently reviewing the electricity transmission charging arrangements as part of its 'Project TransmiT' (compare Ofgem, 2010, and Redpoint Energy, 2011). The German electricity regulator *Bundesnetzagentur* has recently commissioned a study on the introduction of locational pricing (see Frontier, 2011). Moreover, the debate in Germany has gained pace after the decision in 2011 to phase out nuclear power, which has put the transmission grid under pressure (see Bundesnetzagentur, 2011). Also, the European authorities exert strong pressure towards an approach using locational pricing between regional markets on the European level. Transmission congestion management is seen as a key element in the efforts by the *European Commission* to establish a fully functioning electricity market in Europe until 2014 (see, e.g., European Parliament, 2009, and European Council, 2011). For this purpose the European energy regulator *Acer* has developed 'Framework Guidelines on Capacity Allocation and Congestion Management for Electricity' (see Acer (2011)) and the so called *Electricity Regulatory Forum*, which was established by the *European Commission* to promote an internal market for energy, has proposed a 'Target Model for Capacity Allocation and Congestion Management' (see Electricity Regulatory Forum, 2011).[16]

Many contributions have extensively analyzed the impact of the different transmission management regimes. Compare, e.g., Joskow and Tirole (2000) and Gilbert, Neuhoff and Newbery (2004) who analyze the effect of different transmission allocation mechanisms on generation spot market conduct. Moreover, Wolak (2011) and Green (2007) estimate the short run welfare loss due to non-locational pricing in California resp. England and Wales. However, all these articles typically focus on short run spot market conduct, leaving aside long run aspects such as investment incentives in transmission and generation facilities. Recently, experts[17] as well as policy makers[18] have increasingly emphasized that for the proper functioning of electricity markets not only short run efficiency, but also long run incentives are of central importance. Moreover, a detailed analysis of the long run perspective seems to be of particular importance in the light of the ongoing debate on

[15]Neuhoff et al. (2011a) and Neuhoff et al. (2011b) show that the introduction of simultaneous market clearing might lead to substantial operational cost savings as well as a reduction in marginal power prices in the majority of the European countries.

[16]To the Electricity Regulatory Forum it is also regularly referred as the 'Florence Forum'.

[17]Baldick, Bushnell, Hobbs and Wolak (2011) argue that 'the energy sector is now facing an unprecedented investment challenge driven by the need to connect large amounts of new generation to the electricity networks to meet climate change targets, while continuing to provide value for money for consumers and security of supply.'

[18]The 2009 EU directive states that 'undistorted market prices would provide an incentive for cross-border interconnections and for investments in new power generation', compare European Parliament (2009).

insufficient incentives in liberalized electricity markets to provide generation investment (see for the 'missing money discussion', Oren, 2005, Hogan, 2005, Cramton and Stoft, 2006, Joskow, 2007, and Cramton and Ockenfels, 2011). Till date, this debate has entirely abstracted from issues arising due to the presence of transmission networks. As we show, in a system with sequential market clearing, investment incentives turn out to be higher than in systems with simultaneous market clearing. As a central message of our findings, policy makers should thus be aware that switching from a system of sequential market clearing to a system of simultaneous market clearing probably has a negative impact on firms' investment incentives. This in turn aggravates the investment problems identified in the literature on missing money, leading to an increased need for adequate measures to overcome these problems.

As pointed out throughout our analysis, the investment outcome closely depends on the structure of transmission financing. So far our analysis of sequential market clearing has only considered a linear transmission fee. However, in some electricity markets non-linear elements in the transmission fee can be found. The effect of such non-linearities critically depends on their specific structure. In the remainder of this section, we discuss the impact of two common non-linearities in the transmission fee.

First, the transmission fee is raised as a lump sum payment per generator.[19] Then the effect on total generation and transmission investment is even stronger compared to a linear transmission tariff. However, investment in baseload capacity is undistorted. With a lump sum transmission fee, no spot market distortion occurs and generation scarcity rents are even larger. Hence, more investment takes place in generation capacity and also the transmission line. Notice that over-investment in transmission capacity always occurs, that is even for $t > k$. Baseload investment takes place efficiently again, as long as the lump sum fee is levied on generators regardless of the generation technology used.

Second, the transmission fee can be conditioned on the spot market outcome.[20] In such a system, the transmission fee is calculated on the basis of the generators' individual contribution to market output during demand peak. This implies that the transmission fee is implicitly conditioned on the spot market realization θ. If the transmission fee is perfectly set, the net revenue a generator receives, that is, the market price minus the transmission fee, is equal to the outcome of a system with simultaneous market clearing. Hence, such a system can lead to the socially optimal investment outcome.

[19]This might be the case when the transmission fee is levied on generators in a way uncorrelated to the system demand. This is, for example, the case with a fee for network connection as the sole source of transmission financing.

[20]E.g., in the British electricity market, one element in the calculation of the transmission fee (i.e., the Transmission Network Use of System or TNUoS charges) is based on the so called 'triad demand'. According to National Grid 'Triad Demand is measured as the average demand on the system over three half hours between November and February (inclusive) in a financial year. These three half hours comprise the half hour of system demand peak and the two other half hours of highest system demand which are separated from system demand peak and each other by at least ten days.' (see http://www.nationalgrid.com/uk/Electricity/SYS/glossary/#tri and http://www.ofgem.gov.uk/Networks/Trans/ElecTransPolicy/Charging/Pages/Charging.aspx)

6 Extensions

Expensive Transmission. Our analysis so far was based on the assumption $t < k$. This assumption implies that the transmission capacity matches the generation capacity under sequential market clearing. If we relax this assumption, the transmission capacity can also be smaller than the generation capacity, $\tilde{L} < \tilde{X}$. Nevertheless, all results established in Lemmata 1 and 2 and proposition 1 (i) and (ii) remain valid. While our results with respect to generation investment do not change, there is not necessarily overinvestment in transmission capacity. The regulator faces two effects when deciding how much transmission capacity to build, that is, a *sunk cost effect* and a *spot market distortion effect*. The *sunk cost effect* captures the fact that generation investment does not depend on the available transmission capacity under sequential market clearing. When expanding transmission capacity, the regulator does not have to take the additional cost of generation investment into account as it is already sunk. The *spot market distortion effect* captures the distortion at the spot market caused by the transmission fee and is detrimental to the *sunk cost effect*. Technically, the effects are derived by subtracting the first-order conditions describing transmission investment under both investment regimes. This is,

$$\overbrace{\int_{\theta_\tau^L}^{\overline{\theta}} \left(P\left(\tilde{L},\theta\right)-c\right) dF\left(\theta\right)-t}^{Sequential\,Market\,Clearing}-\overbrace{\int_{\theta^L}^{\overline{\theta}} \left(P\left(\tilde{L},\theta\right)-c\right) dF\left(\theta\right)-\left(k+t\right)}^{Simultaneous\,Market\,Clearing}$$

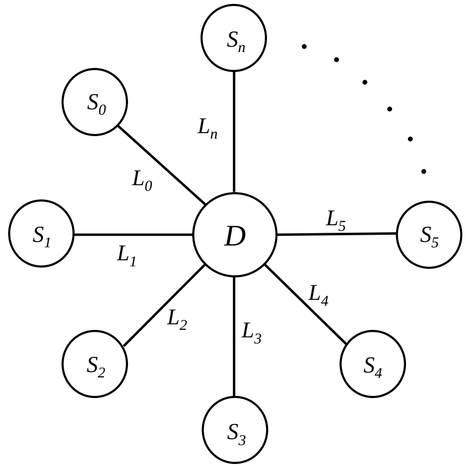
$$= \underbrace{-\int_{\theta^L}^{\theta_\tau^L} \left(P\left(\tilde{L},\theta\right)-c\right) dF\left(\theta\right)}_{spot\,market\,distortion\,effect}+\underbrace{k}_{sunk\,cost\,effect}.$$

Notice that both effects are independent from each other. Hence, one or the other effect can be larger. If the *sunk cost effect* exceeds the *spot market distortion effect*, the transmission capacity is smaller than under simultaneous market clearing $\left(\tilde{L} < \hat{L}\right)$, otherwise it is larger $\left(\tilde{L} > \hat{L}\right)$. Notice that the *sunk cost effect* is clearly larger than the *spot market distortion effect* for $t < k$, and hence, overinvestment in transmission capacity $\left(\tilde{L} > \hat{L}\right)$ occurs.

Complex Networks. In this section, we show that our results from section 4 for a two-node network can be easily generalized to more complex networks. In principle, our findings hold for any star-network with an arbitrarily large number of nodes. An example for such a network with n nodes is presented in Figure 3. We illustrate this generalization in the simplest possible star-network with one demand and two supply nodes.[21] We assume that the cost of transmission

[21]Since the use of different generation technologies is often restricted to certain geographical locations or nodes in the network, we consider a situation, where all the baseload generation is located at one of the two supply nodes, while all the peakload generation is located at the other supply node. Wind turbines or solar panels can only be used at sufficiently windy or sunny locations, gas-fired power plants require access to a gas pipeline, lignite-, coal- and nuclear-fired plants need access to large quantities of water. Moreover, the transport of lignite and coal is rather costly, so that access to transport facilities is required and the location of nuclear-fired plants has to fulfill certain safety regulations.

Figure 3: n-node star network



investment t is identical for both transmission lines. Moreover, we denote the capacity of the transmission line connecting the 'baseload node' with the demand node by L_1 and the sum of transmission line capacities by L. The capacity of the transmission line connecting the 'peakload node' with the demand node is given by $L - L_1 = L_0$. Thus, the only difference between the three-node network and the two-node network lies in the fact that the baseload generators are connected to the demand node via a separate line, where congestion can occur independently of the peakload line. In the subsequent analysis we focus on why this is irrelevant and does not change our results.

With simultaneous market clearing - as before -, both transmission line capacities exactly match the generation capacities at the respective supply nodes $\left(\hat{L} = \hat{X},\, \hat{L_1} = \hat{X}_1\right)$. Moreover, though both generation technologies are connected via different transmission lines, which can be congested independently from each other, baseload investment can again be expressed as a replacement trade-off independent from the cost of transmission. In other words, under simultaneous market clearing, the contribution of a generation unit to transmission financing is independent of the generation technology used. Replacing a peakload unit with a baseload unit makes additional baseload transmission capacity necessary. However, the same amount of transmission capacity becomes superfluous at the peakload node. Hence, the total transmission capacity in the network remains unchanged. Notice that in equilibrium the marginal value of transmission has to be equal for both lines as the marginal cost of transmission investment t is the same for both lines. This implies that both transmission lines are built such that the resulting total scarcity rents at each line times the probability of congestion are identical. Since the total scarcity rents from the baseload technology are higher than those from the peakload technology, it has to hold that the baseload line is less often congested relative to the peakload line.

The following remark compares the investment performance under simultaneous market clearing with the socially optimal investment outcome which is denoted by (X^*, X_1^*, L^*, L_1^*).

Remark 2 *[Generation and Transmission Investment - Simultaneous Market Clearing] The solution obtained under a system with simultaneous market clearing gives rise to the socially optimal investment in the base load technology* $\left(\hat{X}_1 = X_1^*\right)$, *in total generation investment* $\left(\hat{X} = X^*\right)$ *as well as in the transmission lines* $\left(\hat{L} = L^*,\, \hat{L}_1 = L_1^*\right)$.

This remark resembles the result stated in remark 1. Hence, simultaneous market clearing also gives efficient investment signals in more complex star-networks.

With sequential market clearing, again, both transmission line capacities exactly match the generation capacities at the respective supply nodes $\left(\tilde{L} = \tilde{X},\, \tilde{L}_1 = \tilde{X}_1\right)$. However, as in a two-node network, the subsequently built generation capacity does not depend on the existence of the transmission capacity. Hence, the size of the transmission lines is solely determined by the generation capacity. This implies that the marginal value of transmission capacity is not necessarily equal among both transmission lines as it was the case under simultaneous market clearing. In the following, we state our main result for the three-node network, which compares industry investment in generation and optimal transmission investment under sequential market clearing with investment under simultaneous market clearing.

Proposition 2 *[Generation and Transmission Investment - Star Network] If demand is inelastic,* $|\eta| \leq 1$, *the solution obtained under a system with sequential market clearing in a star-network with* 3 *nodes gives rise to the identical investment outcome as described in Proposition 1. That is, sequential market clearing leads to* (*i*) *higher total investment,* $\tilde{X} > \hat{X}$, (*ii*) *lower investment in baseload generation capacity,* $\tilde{X}_1 < \hat{X}_1$, *as well as* (*iii*) *higher transmission capacity,* $\tilde{L} > \hat{L}$, *compared to investment under simultaneous market clearing.*

Proof. See Appendix. ■

This proposition supports the results in Proposition 1 for the two-node network and shows that our findings from Section 4 can be easily generalized to more complex star-networks.

7 Conclusion

Market design is important in network industries as potential congestion between different locations can create a significant barrier to trade. In this regard, there are two competing approaches: Either, the whole network is designed as a single market with only one price, where potential network congestion is treated through an alternative mechanism outside the market, or different prices are introduced at different locations, which can take potential congestion into account. A prominent example for such a problem is given by the management of transmission capacity in liberalized electricity markets. In the U.S. most markets already implemented simultaneous market clearing, but in Europe sequential market clearing is still used in the vast majority of electricity markets. However, the rapid replacement of old carbon intense power plants by new and low carbon generation puts the transmission grid under pressure. Old and new generation facilities are typically not located at the same production site. This is because different production technologies often have different locational requirements. That is, e.g., gas-fired power plants need access to gas pipelines, while wind turbines are only efficient to use in windy areas. This creates the need for an efficient utilization of the existing transmission capacity. While many contributions exist on the short run effects on transmission management, experts and policymakers have highlighted the need for the proper long run investment incentives in generation and transmission capacity for the efficient functioning of the electricity sector. This paper sheds light on the long run effects of different transmission management rules by introducing a network model with endogenous generation and transmission capacities. We analyze the impact of two regularly used market designs - simultaneous and sequential market clearing - on generation and transmission capacities as well as on the generation technology mix in the market.

First, we find that simultaneous market clearing leads to the socially optimal generation and transmission capacity as well as to the optimal technology mix. This confirms results from the previous literature (see, for example, Joskow and Tirole (2005)).
Second, we find that sequential market clearing leads to overinvestment in total generation and transmission capacity. Sequential market clearing disentangles the price signal from the location of production and hence, from its locational marginal value. This leads to exaggerated investment incentives.
Third, we find that under sequential market clearing the technology mix is distorted, that is, overinvestment in peakload capacity and underinvestment in baseload capacity takes place. This is because baseload generators contribute more to financing the transmission network than peakload generators and hence, investment in baseload becomes less lucrative.

The central message of our findings is that policy makers should be aware that switching from a system of sequential market clearing to a system of simultaneous market clearing has a negative impact on firms' investment incentives. This in turn aggravates potential investment problems stemming from market imperfections and institutional constraints in electricity markets, which have been identified in the literature on missing money. This might lead to an increased need for adequate measures to overcome those problems.

References

Acer (2011): "Framework Guidelines on Capacity Allocation and Congestion Management for Electricity," *Agency for the Cooperation of Energy Regulators*, FG-2011-E-002.

Baldick, R., J. Bushnell, B. Hobbs, and F. Wolak (2011): "Optimal Charging Arrangements for Energy Transmission: Final Report," *Report Prepared for and Commissioned by Project TransmiT, Great Britain Office of Gas & Electricity Markets*.

Boom, A. (2009): "Vertically integrated Firms Investments in Electricity Generating Capacity," *International Journal of Industrial Organization*, 27 (4), 544–551.

Bundesnetzagentur (2011): "Auswirkungen des Kernkraft-Moratoriums auf die Übertragungsnetze und Versorgungssicherheit. Bericht der Bundesnetzagentur an das Bundesministerium für Wirtschaft und Technologie," Bundesnetzagentur.

Bushnell, J. (1999): "Transmission Rights and Market Power," *The Electricity Journal*, 12 (8), 77–85.

Bushnell, J., and S. Stoft (1997): "Improving Private Incentives for Electric Grid Investment," *Ressource and Energy Economics*, 19, 85–108.

Cramton, P., and A. Ockenfels (2011): "Economics and design of capacity markets for the power sector," *Working Paper, University of Maryland*.

Cramton, P., and S. Stoft (2006): "The Convergence of Market Designs for Adequate Generating Capacity," *White Paper, California Electricity Oversight Board*.

Crew, M., C. Fernando, and P. Kleindorfer (1995): "The Theory of Peak-Load Pricing: A Survey.," *Journal of Regulatory Economics*, 8 (3), 215–248.

Electricity Regulatory Forum (2011): "Proposal for Target Model and Roadmap for Capacity Allocation and Congestion Management," Electricity Regulatory Forum.

European Council (2011): "Conclusions of the European Council (4 February 2011)," EUCO 2/1/11 REV 1.

European Parliament (2009): "Directive 2009/72/EC of the European Parliament and of the Council," *Official Journal of the European Union*, L 211/56.

Fabra, N., and M. A. de Frutos (2011): "Endogenous capacities and price competition: The role of demand uncertainty," *International Journal of Industrial Organization*, 29 (4), 399–411.

Fabra, N., N.-H. von der Fehr, and M. Ángeles de Frutos (2011): "Market Design and Investment Incentives," *Economic Journal*, 121, 1340–1360.

Frontier Economics (2011): "Bedeutung von etablierten nationalen Gebotszonen für die Integration des europäischen Strommarkts - ein Ansatz zur wohlfahrtsorientierten Beurteilung," *Frontier Economics*.

Gabszewicz, J., and S. Poddar (1997): "Demand Fluctuations and Capacity Utilization under Duopoly," *Economic Theory*, 10 (1), 131–146.

Gilbert, R., K. Neuhoff, and D. Newbery (2004): "Allocation Transmission to Mitigate Market Power in Electricity Networks," *The RAND Journal of Economics*, 35 (4), 691–709.

Green, R. (2007): "Nodal pricing of electricity: how much does it cost to get it wrong?," *Journal of Regulatory Economics*, 31 (2), 125–149.

Hogan, W. (1992): "Contract networks for electric power transmission," *Journal of Regulatory Economics*, 4 (3), 211–242.

——— (1999): "Restructuring the Electricity Market: Institutions for Network Systems," *Harvard University, Cambridge, MA*.

——— (2005): "On an Energy Only Electricity Market Design for Resource Adequacy," *Harvard University, Cambridge, MA*.

Hogan, W., J. Rosellón, and I. Vogelsang (2010): "Toward a combined merchant- regulatory mechanism for electricity transmission expansion," *Journal of Regulatory Economics*, 38 (2), 1–31.

Joskow, P. (2007): *The New Energy Paradigm,*chap. Competitive Electricity Markets and Investment in New Generating Capacity, pp. 76–122. Oxford University Press.

Joskow, P., and J. Tirole (2000): "Transmission rights and market power on electric power networks," *The RAND Journal of Economics*, 31 (3), 450–487.

——— (2005): "Merchant Transmission Investment," *Journal of Industrial Economics*, 53 (2), 233–264.

Lijsen, M. (2006): "The Real Time Price Elasticity of Electricity," *Energy Economics*, 29, 249–258.

Léautier, T. (2000): "Regulation of an electric power transmission company," *The Energy Journal*, 21 (4), 61–92.

Murphy, F., and Y. Smeers (2005): "Generation Capacity Expansion in Imperfectly Competitive Restructured Electricity Markets," *Operations Research*, 53, 646–661.

Neuhoff, K., R. Boyd, T. Grau, J. Barquin, F. Echavarren, J. Bialek, C. Dent, C. von Hirschhausen, B. Hobbs, F. Kunz, H. and Christian Nabe, G. Papaefthymiou, and C. Weber (2011b): "Renewable Electric Energy Integration: Quantifying the Value of Design of Markets for International Transmission Capacity," *DIW Discussion Papers*, 1166.

Neuhoff, K., B. Hobbs, and D. Newbery (2011a): "Congestion Management in European Power Networks: Criteria to Assess the Available Options," *DIW Discussion Papers*, 1161.

Ofgem (2010): "Project TransmiT: A Call for Evidence," *Office for Gas and Electricity Markets*, 119/10.

O'Neill, R., U. Helman, and B. Hobbs (2008): *Competitive Electricity Markets: Design, Implementation, Performance,*chap. The Design of U.S. Wholesale Energy and Ancillary Service Auction markets: Theory and Practice, pp. 179–244. Global Energy Policy and Economics Series, Elsevier.

O'Neill, R., U. Helman, B. Hobbs, and R. Baldick (2006): *Electricity Market Reform: An International Perspective,*chap. Independent system operators in the United States: History, lessons learned, and prospects, pp. 479–528. Global Energy Policy and Economics Series, Elsevier.

Oren, S. (2005): *Electricity Deregulation: Choices and Challenges,*chap. Generation Adequacy in Competitive Electricity Markets, pp. 388–414. University of Chicago Press.

Redpoint Energy (2011): "Modelling the Impact of Transmission Charging Options," *Redpoint Energy Ltd.*

Reynolds, S., and B. Wilson (2000): "Bertrand Edgeworth Competition, Demand Uncertainty, and Asymmetric Outcomes," *Journal of Economic Theory*, 92, 122–141.

Rious, V., J.-M. Glachant, and P. Dessante (2010): "Transmission Network Investment as an Anticipation Problem," *RSCAS Working Papers*, 2010/04.

Sauma, E., and S. Oren (2009): "Do Generation Firms in Restructured Electricity Markets Have Incentives to Support Social-Welfare-Improving Transmission Investments?," *Energy Economics*, 31 (5), 676–689.

Sauma, E. E., and S. S. Oren (2006): "Proactive planning and valuation of transmission investments in restructured electricity markets," *Journal of Regulatory Economics*, 30, 358–387.

Schaber, K., F. Steinke, and T. Hamacher (2012): "Transmission grid extensions for the integration of variable renewable energies in Europe. Who benefits where?," *Energy Policy*, 43, 123–135.

Vogelsang, I. (2001): "Price regulation for independent transmission companies," *Journal of Regulatory Economics*, 20, 141–165.

Wolak, F. (2011): "Measuring the Benefits of Greater Spatial Granularity in Short-Term Pricing in Wholesale Electricity Markets," *American Economic Journal: Papers and Proceedings*, 101 (3), 247–252.

Zöttl, G. (2011): "On Optimal Scarcity Prices," *International Journal of Industrial Organization*, 29 (5), 589–605.

Appendix

A Preliminary definitions

(I) **Feasible capacity.** Φ describes the feasible capacity and Φ_1 describes the feasible baseload capacity in the market. It is given by

$$\Phi = \begin{cases} X, & if\, X \leq L \\ L, & if\, X > L \end{cases}, \qquad \Phi_1 = \begin{cases} X_1, & if\, X_1 \leq L \\ L, & if\, X_1 > L \end{cases}.$$

The feasible peakload capacity is given by $\Phi - \Phi_1$.

(II) **Spot market definitions.** The different critical spot market realizations are defined as follows.

$$\begin{array}{llll}
\theta^{\underline{X_1}}: & P\left(X_1, \theta^{\underline{X_1}}\right) - c_1 = 0, & \theta_\tau^{\underline{X_1}}: & P\left(X_1, \theta_\tau^{\underline{X_1}}\right) - (c_1 + \tau) = 0 \\
\theta^{\overline{X_1}}: & P\left(X_1, \theta^{\overline{X_1}}\right) - c = 0, & \theta_\tau^{\overline{X_1}}: & P\left(X_1, \theta_\tau^{\overline{X_1}}\right) - (c_1 + \tau) = 0 \\
\theta^{X}: & P\left(X, \theta^{X}\right) - c = 0, & \theta_\tau^{X}: & P\left(X, \theta_\tau^{X}\right) - (c_1 + \tau) = 0 \\
\theta^{L}: & P\left(L, \theta^{L}\right) - c = 0, & \theta_\tau^{L}: & P\left(L, \theta_\tau^{L}\right) - (c_1 + \tau) = 0 \\
\theta^{\underline{M_1}}: & P\left(\Phi_1, \theta^{\underline{M_1}}\right) - c_1 = 0, & \theta^{\tau}: & P\left(0, \theta^{\tau}\right) - (c_1 + \tau) = 0 \\
\theta^{\overline{M_1}}: & P\left(\Phi_1, \theta^{\overline{M_1}}\right) - c = 0, & \theta^{M}: & P\left(\Phi, \theta^{M}\right) - c = 0
\end{array}$$

Remember that the actual size T of the transmission line differs from the nominal size L. The frequency of the capacity is denoted by $g(T)$, its support is given by $[-\epsilon, +\epsilon]$, and its cumulative distribution is denoted by $G(T)$. If the size of the transmission and generation capacities is sufficiently different, that is, $\mid X - L \mid > \epsilon$, the former (latter) is larger (smaller) with probability 1 (0). However, if transmission and generation capacities are sufficiently close, the uncertainty of the transmission line also affects the relative size of the generation and transmission capacities. $G(.)$ is the probability that the transmission line is binding before the generation capacity is and $1 - G(.)$ is the probability that the generation capacity is binding before the transmission line is doing so. Formally, we assign the following probabilities

$$G(X - L) = \begin{cases} 0, & if\, L - X > \epsilon \\ 1, & if\, X - L > \epsilon \\ (0,1), & otherwise \end{cases}$$

(III) **Spot market profits and welfare under simultaneous market clearing.** In this section we present the profits of generators and transmission owners as well as welfare for different spot markets. $W(X, X_1, L, \theta)$ denotes the economy's welfare and $\pi_i(x, x_1, l, \theta)$ the profit of a generator.

• at spot markets $\theta\epsilon\left[\underline{\theta},\theta^{\underline{M_1}}\right]$

$$
\begin{aligned}
W\left(X,X_1,L,\theta\right) &= \int_0^Q \left(P\left(v,\theta\right)-c_1\right)dv \\
\pi\left(x,x_1,l,\theta\right) &= 0
\end{aligned}
$$

• at spot markets $\theta\epsilon\left[\theta^{\underline{M_1}},\theta^{\overline{M_1}}\right]$

$$
\begin{aligned}
W\left(X,X_1,L,\theta\right) &= \left(1-G\left(X_1-L\right)\right)\int_0^{X_1}\left(P\left(v,\theta\right)-c_1\right)dv+G\left(X_1-L\right)\int_0^{L}\left(P\left(v,\theta\right)-c_1\right)dv \\
\pi\left(x,x_1,l,\theta\right) &= \left(1-G\left(X_1-L\right)\right)\left(P\left(X_1,\theta\right)-c_1\right)x_1
\end{aligned}
$$

• at spot markets $\theta\epsilon\left[\theta^{\overline{M_1}},\theta^{M}\right]$

$$
\begin{aligned}
W\left(X,X_1,L,\theta\right) &= \left(1-G\left(X_1+Q-L\right)\right)\left(\int_0^{X_1+Q}P\left(v,\theta\right)dv-\int_0^{X_1}c_1dv-\int_{X_1}^{X_1+Q}cdv\right) \\
&\quad +G\left(X_1+Q-L\right)\left(\int_0^{L}P\left(v,\theta\right)dv-\int_0^{X_1}c_1dv-\int_{X_1}^{L}cdv\right) \\
\pi\left(x,x_1,l,\theta\right) &= \left(1-G\left(X_1+Q-L\right)\right)\left(P\left(X_1+Q,\theta\right)-c_1\right)x_1+G\left(X_1+Q-L\right)\left(c-c_1\right)x_1
\end{aligned}
$$

• at spot markets $\theta\epsilon\left[\theta^{M},\overline{\theta}\right]$

$$
\begin{aligned}
W\left(X,X_1,L,\theta\right) &= \left(1-G\left(X-L\right)\right)\left(\int_0^{X}P\left(v,\theta\right)dv-\int_0^{X_1}c_1dv-\int_{X_1}^{X}cdv\right) \\
&\quad +G\left(X-L\right)\left(\int_0^{L}P\left(v,\theta\right)dv-\int_0^{X_1}c_1dv-\int_{X_1}^{L}cdv\right) \\
\pi\left(x,x_1,l,\theta\right) &= \left(1-G\left(X-L\right)\right)\left(\left(P\left(X,\theta\right)-c_1\right)x_1+\left(P\left(X,\theta\right)-c\right)\left(x-x_1\right)\right) \\
&\quad +G\left(\left(X-L\right)\right)\left(c-c_1\right)x_1
\end{aligned}
$$

(IV) **Spot market profits and welfare under sequential market clearing.** In this section we present the profits of generators and transmission owners as well as welfare for different spot markets. $W\left(X,X_1,L,\theta\right)$ denotes the economy's welfare and $\pi_i\left(x,x_1,l,\theta\right)$ the profit of a generator at spot market realization θ. Notice that welfare under sequential market clearing only differs from welfare in simultaneous market clearing as the generators' choice variables $Q\left(\tau\left(L\right)\right)$, $X_1\left(\tau\left(L\right)\right)$ and $X\left(\tau\left(L\right)\right)$ are now depending on the transmission fee $\left(\tau\left(L\right)\right)$ which has to be taken into account. In addition, the critical spot market realizations are also affected by the transmission fee.

• at spot markets $\theta\epsilon\left[\underline{\theta},\theta_{\tau}^{\underline{M_1}}\right]$

$$
\begin{aligned}
W\left(X,X_1,L,\theta\right) &= \int_0^{Q(\tau(L))}\left(P\left(v,\theta\right)-c_1\right)dv \\
\pi\left(x,x_1,l,\theta\right) &= 0
\end{aligned}
$$

- at spot markets $\theta \epsilon \left[\theta_{\tau}^{\underline{M_1}}, \theta_{\tau}^{\overline{M_1}}\right]$

$$\begin{aligned}W\left(X, X_1, L, \theta\right) &= \left(1 - G\left(X_1 - L\right)\right)\int_0^{X_1(\tau(L))}\left(P\left(v,\theta\right) - c_1\right)dv + G\left(X_1 - L\right)\int_0^{L}\left(P\left(v,\theta\right) - c_1\right)dv \\ \pi\left(x, x_1, l, \theta\right) &= \left(P\left(X_1, \theta\right) - c_1\right)x_1\end{aligned}$$

- at spot markets $\theta \epsilon \left[\theta_{\tau}^{\overline{M_1}}, \theta_{\tau}^{M}\right]$

$$\begin{aligned}W\left(X, X_1, L, \theta\right) &= \left(1 - G\left(X_1 + Q - L\right)\right)\left(\int_0^{X_1(\tau(L))+Q(\tau(L))} P\left(v,\theta\right)dv - \int_0^{X_1(\tau(L))} c_1 dv - \int_{X_1(\tau(L))}^{X_1(\tau(L))+Q(\tau(L))} c dv\right) \\ &\quad + G\left(X_1 + Q - L\right)\left(\int_0^{L} P\left(v,\theta\right)dv - \int_0^{X_1(\tau(L))} c_1 dv - \int_{X_1(\tau(L))}^{L} c dv\right) \\ \pi\left(x, x_1, l, \theta\right) &= \left(P\left(X_1 + Q, \theta\right) - c_1\right)x_1\end{aligned}$$

- at spot markets $\theta \epsilon \left[\theta_{\tau}^{M}, \overline{\theta}\right]$

$$\begin{aligned}W\left(X, X_1, L, \theta\right) &= \left(1 - G\left(X - L\right)\right)\left(\int_0^{X(\tau(L))} P\left(v,\theta\right)dv - \int_0^{X_1(\tau(L))} c_1 dv - \int_{X_1(\tau(L))}^{X(\tau(L))} c dv\right) \\ &\quad + G\left(X - L\right)\left(\int_0^{L} P\left(v,\theta\right)dv - \int_0^{X_1(\tau(L))} c_1 dv - \int_{X_1(\tau(L))}^{L} c dv\right) \\ \pi\left(x, x_1, l, \theta\right) &= \left(P\left(X, \theta\right) - c_1\right)x_1 + \left(P\left(X,\theta\right) - c\right)\left(x - x_1\right)\end{aligned}$$

B Proof of remark 1

(I) **Welfare and first order conditions.** The previous results enable us to derive overall welfare. It is obtained by the integral over all spot markets.

$$W\left(X, X_1, L\right) = \int_{\underline{\theta}}^{\overline{\theta}} W\left(X, X_1, L, \theta\right)dF\left(\theta\right) - k_1 x_1 - k\left(x - x_1\right) - tl$$

Note that the integrand in this expression is continuous in θ. The first derivatives are given by:

$$\begin{aligned}
W_X &= (1-G(X-L))\int_{\theta^M}^{\overline{\theta}} (P(X,\theta)-c)\,dF(\theta)-k \\
W_{X_1} &= (1-G(X_1-L))\int_{\theta^{\underline{M_1}}}^{\theta^{\overline{M_1}}} (P(X_1,\theta)-c_1)\,dF(\theta)+\int_{\theta^{\overline{M_1}}}^{\theta^M} (P(X_1+Q,\theta)-c_1)\,dF(\theta) \\
&\quad +\int_{\theta^M}^{\overline{\theta}} (c-c_1)\,dF(\theta)-(k-k_1) \\
W_L &= G(X_1-L)\int_{\theta^{\underline{M_1}}}^{\theta^{\overline{M_1}}} (P(L,\theta)-c_1)\,dF(\theta)+G(X_1+Q-L)\int_{\theta^{\overline{M_1}}}^{\theta^M} (P(L,\theta)-c)\,dF(\theta) \\
&\quad +G(X-L)\int_{\theta^M}^{\overline{\theta}} (P(L,\theta)-c)\,dF(\theta)-t
\end{aligned}$$

(II) **Equilibrium.** In equilibrium the first derivatives have to be equal to zero. Hence, the transmission line and total generation capacity have to be of the same size:

$$X^* = L^*$$

This is

$$W_X(X^*,X_1^*,L^*)+W_L(X^*,X_1^*,L^*) = \int_{\theta^X}^{\overline{\theta}} (P(X^*,\theta)-c)\,dF(\theta)-(k+t)=0 \quad (1)$$

$$W_{X_1}(X^*,X_1^*,L^*) = \int_{\theta^{\underline{X_1}}}^{\theta^{\overline{X_1}}} (P(X_1^*,\theta)-c_1)\,dF(\theta)+\int_{\theta^{\overline{X_1}}}^{\overline{\theta}} (c-c_1)\,dF(\theta)-(k_1-k)=0 \quad (2)$$

(III) **Uniqueness.** As in equilibrium $X^*=L^*$ has to hold, it is sufficient to check the second order conditions only for the joint equilibrium conditions from (II) with respect to X and X_1. The second derivatives are given by

$$\begin{aligned}
W_{XX}(X^*,X_1^*,L^*)+W_{LL}(X^*,X_1^*,L^*) &= \int_{\theta^X}^{\overline{\theta}} P_q(X^*,\theta)\,dF(\theta)<0 \\
W_{X_1X_1}(X^*,X_1^*,L^*) &= \int_{\theta^{\underline{X_1}}}^{\theta^{\overline{X_1}}} P_q(X_1^*,\theta)+\int_{\theta^{\overline{X_1}}}^{\theta^X} P_q(X_1^*+Q,\theta)<0 \\
W_{XX_1}(X^*,X_1^*,L^*) &= 0
\end{aligned}$$

It is easy to see that the absolute value of the cross derivatives is smaller than the absolute value of any of the second derivatives

$$\mid W_{xx}(X,X_1,L)\mid,\mid W_{x_1x_1}(X,X_1,L)\mid>\mid W_{xx_1}(X,X_1,L)\mid$$

Hence, the product of the cross derivatives is smaller than the product of the second derivatives:

$$\pi_{xx}(X,X_1,L)\cdot\pi_{x_1x_1}(X,X_1,L)>0$$

That is, the first order conditions describe a unique equilibrium.

C Proof of Lemma 1

(I) **Preliminaries: Profits and first order conditions.** The results for the spot market equilibria enable us to derive the investors' overall profits. It is obtained by the integral over all spot markets. For generators this is given by:

$$\pi_i(x, x_1, l) = \int_{\underline{\theta}}^{\overline{\theta}} \pi_i(x, x_1, l, \theta)\, dF(\theta) - k_1 x_1 - k(x - x_1) \tag{3}$$

Note that the integrand in this expression is continuous in θ. The first derivatives are given by:

$$\begin{aligned}
\pi_x &= (1 - G(X - L)) \int_{\theta^M}^{\overline{\theta}} (P(X, \theta) - c)\, dF(\theta) - k \\
\pi_{x_1} &= (1 - G(X_1 - L)) \int_{\underline{\theta^{M_1}}}^{\theta^{\overline{M_1}}} (P(X_1, \theta) - c_1)\, dF(\theta) + (1 - G(X_1 + Q - L)) \int_{\theta^{\overline{M_1}}}^{\theta^M} (P(X_1 + Q, \theta) - c_1)\, dF(\theta) \\
&\quad + G(X_1 + Q - L) \int_{\theta^{\overline{M_1}}}^{\theta^M} (c - c_1)\, dF(\theta) - (k_1 - k)
\end{aligned}$$

The first derivative with respect to the optimal transmission line is already given in the proof of 1:

$$\begin{aligned}
W_L &= G(X_1 - L) \int_{\underline{\theta^{M_1}}}^{\theta^{\overline{M_1}}} (P(L, \theta) - c_1)\, dF(\theta) + G(X_1 + Q - L) \int_{\theta^{\overline{M_1}}}^{\theta^M} (P(L, \theta) - c)\, dF(\theta) \\
&\quad + G(X - L) \int_{\theta^M}^{\overline{\theta}} (P(L, \theta) - c)\, dF(\theta) - t
\end{aligned}$$

(II) **Equilibrium.** The equilibrium equates the first derivatives to zero. Hence, in equilibrium, transmission and generation capacity have to be of equal size:

$$\hat{X} = \hat{L}$$

This is

$$\pi_X = \left(1 - G\left(\hat{X} - \hat{L}\right)\right) \int_{\theta^X}^{\overline{\theta}} \left(P\left(\hat{X}, \theta\right) - c\right) dF(\theta) - k = 0 \tag{4}$$

$$\pi_{X_1} = \int_{\underline{\theta^{X_1}}}^{\theta^{\overline{X_1}}} \left(P\left(\hat{X}_1, \theta\right) - c_1\right) dF(\theta) + \int_{\theta^{\overline{X_1}}}^{\overline{\theta}} (c - c_1)\, dF(\theta) - (k_1 - k) = 0 \tag{5}$$

$$W_L = G\left(\hat{X} - \hat{L}\right) \int_{\theta^X}^{\overline{\theta}} \left(P\left(\hat{L}, \theta\right) - c\right) dF(\theta) - t = 0 \tag{6}$$

Comparing equations (4), (5) and (6) with the first order conditions of the socially optimal investment (1) and (2), it is straightforward to see that investment under simultaneous market clearing leads to the socially optimal investment outcome.

(III) **Uniqueness.** As the first oder conditions are identical to the first order conditions characterizing the socially optimal investment (remark 1). As we have shown, these characterize a unique equilibrium. Hence, also the first order conditions under (II) do.

D Proof of Lemma 2

D.1 Preliminaries: Balanced Budget

We assume that the regulator has to fulfill the following budget balancing equation:

$$\begin{aligned} BB: \quad & -tL - \int_{\theta_\tau^L}^{\theta_\tau^X} \int_L^{Q^*(\tau(L),\theta)} \left(P\left(L,\theta\right) - c - \tau\left(L\right)\right) dydF\left(\theta\right) - \int_{\theta_\tau^X}^{\overline{\theta}} \int_L^{X(\tau(L))} \left(P\left(L,\theta\right) - c - \tau\left(L\right)\right) dydF\left(\theta\right) \\ & + \int_{\theta^\tau}^{\theta_\tau^{\underline{X_1}}} Q^\tau\left(\tau\left(L\right),\theta\right)\tau\left(L\right) dF\left(\theta\right) + \int_{\theta_\tau^{\underline{X_1}}}^{\theta_\tau^{\overline{X_1}}} X_1\left(\tau\left(L\right)\right)\tau\left(L\right) dF\left(\theta\right) + \int_{\theta_\tau^{\overline{X_1}}}^{\theta_\tau^L} \left(X_1\left(\tau\left(L\right)\right) + Q^*\left(\tau\left(L\right)\right)\right)\tau\left(L\right) dF\left(\theta\right) \\ & + \int_{\theta_\tau^L}^{\bar{\theta}} L\tau\left(L\right) dF\left(\theta\right) = 0 \end{aligned} \tag{7}$$

This equation implies that the revenues from the transmission fee are identical to the expenditures for the investment cost as well as the cost to run the adjustment market.

D.2 Market generation investment

(I) **Preliminaries: Profits and first order conditions.** The results for the spot market equilibria enable us to derive the investors' overall profits. It is obtained by the integral over all spot markets. For generators this is given by:

$$\pi_i\left(x^B, x^P, l\right) = \int_{\underline{\theta}}^{\overline{\theta}} \pi_i\left(x^B, x^P, l, \theta\right) dF\left(\theta\right) - k_1 x_1 - k\left(x - x_1\right) \tag{8}$$

Note that the integrand in this expression is continuous in θ. The first derivatives are given by:

$$\begin{aligned} \pi_x\left(x, x_1, l\right) &= \int_{\theta_\tau^X}^{\overline{\theta}} \left(P\left(X,\theta\right) - \tau - c\right) dF\left(\theta\right) - k \\ \pi_{x_1}\left(x, x_1, l\right) &= \int_{\theta_\tau^{\underline{X_1}}}^{\theta_\tau^{\overline{X_1}}} \left(P\left(X_1,\theta\right) - \tau - c_1\right) dF\left(\theta\right) + \int_{\theta_\tau^{\overline{X_1}}}^{\theta_\tau^X} \left(P\left(X_1 + Q,\theta\right) - \tau - c_1\right) dF\left(\theta\right) \\ &\quad + \int_{\theta_\tau^X}^{\overline{\theta}} \left(c - c_1\right) dF\left(\theta\right) - \left(k_1 - k\right) \end{aligned}$$

(II) **Equilibrium.** The equilibrium equates the first derivatives to zero. This is

$$\tilde{X} \quad : \quad \int_{\theta_\tau^X}^{\overline{\theta}} \left(P\left(\tilde{X},\theta\right) - \tau - c\right) dF\left(\theta\right) - k = 0 \tag{9}$$

$$\tilde{X}_1 \quad : \quad \int_{\theta_\tau^{\underline{X_1}}}^{\theta_\tau^{\overline{X_1}}} \left(P\left(\tilde{X}_1,\theta\right) - \tau - c_1\right) dF\left(\theta\right) + \int_{\theta_\tau^{\overline{X_1}}}^{\overline{\theta}} \left(c - c_1\right) dF\left(\theta\right) - \left(k_1 - k\right) = 0 \tag{10}$$

(III) **Uniqueness.** The second derivatives are given by

$$
\begin{aligned}
\pi_{x_1x_1}(x, x_1, l) &= \int_{\theta_\tau^{\underline{X_1}}}^{\theta_\tau^{\overline{X_1}}} 2P_q\left(\tilde{X}_1, \theta\right) dF(\theta) + \int_{\theta_\tau^{\overline{X_1}}}^{\theta_\tau^{X}} 2P_q\left(\tilde{X}_1 + Q, \theta\right) dF(\theta) < 0 \\
\pi_{xx}(x, x_1, l) &= \int_{\theta_\tau^{X}}^{\bar{\theta}} 2P_q\left(\tilde{X}, \theta\right) dF(\theta) < 0 \\
\pi_{xx_1}(x, x_1, l) &= 0
\end{aligned}
$$

As is easy to see, the absolute value of the cross derivatives is smaller than the absolute value of any of the second derivatives and hence, the product of the cross derivatives is smaller than the product of the second derivatives

$$\mid \pi_{xx_1}(x, x_1, l) \mid < \mid \pi_{xx}(x, x_1, l) \mid, \mid \pi_{x_1x_1}(x, x_1, l) \mid$$

$$\pi_{xx}(x, x_1, l) \cdot \pi_{x_1x_1}(x, x_1, l) > 0.$$

That is, the first order conditions describe a unique equilibrium.

D.3 Optimal transmission line investment

(I) **Welfare.** The results for the spot market welfare enable us to derive the investors' overall profits. It is obtained by the integral over all spot markets. Welfare is given by

$$W(X, X_1, L) = \int_{\underline{\theta}}^{\bar{\theta}} W(X, X_1, L, \theta)\, dF(\theta) - k\left(X(\tau(L)) - X_1(\tau(L))\right) - k_1 X_1(\tau(L)) - tL \tag{11}$$

Taking the first derivative and rearranging gives:

$$
\begin{aligned}
W_L = & \int_{\underline{\theta}}^{\theta_\tau^{\underline{X_1}}} \tau(L)\, Q_\tau^*(\tau(L))\, \tau_L(L)\, dF(\theta) + \int_{\theta_\tau^{\underline{X_1}}}^{\theta_\tau^{\overline{X_1}}} \left(P\left(X_1(\tau(L)), \theta\right) - c_1\right) X_{1\tau}(\tau(L))\, \tau_L(L)\, dF(\theta) \\
& + \int_{\theta_\tau^{\overline{X_1}}}^{\theta_\tau^{L}} \tau(L)\left(X_{1\tau}(\tau(L)) + Q_\tau^*(\tau(L))\right) \tau_L(L)\, dF(\theta) + \int_{\theta_\tau^{\overline{X_1}}}^{\bar{\theta}} (c - c_1)\, X_{1\tau}(\tau(L))\, \tau_L(L)\, dF(\theta) \\
& + \int_{\theta_\tau^{L}}^{\bar{\theta}} (P(L, \theta) - c)\, dF(\theta) - kX_\tau(\tau(L))\, \tau_L(L) - (k_1 - k)\, X_{1\tau}(\tau(L))\, \tau_L(L) - t
\end{aligned}
$$

(II) **Balanced Budget.** Taking the first derivative of the budget balancing equation and rearranging gives

$$\begin{aligned} BB_L = \quad & \int_{\theta^{\tau}}^{\theta_{\tau}^{\underline{X_1}}} \tau(L) Q_{\tau}^{\tau}(\tau(L),\theta)\tau_L(L)\,dF(\theta) + \int_{\theta_{\tau}^{\underline{X_1}}}^{\theta_{\tau}^{\overline{X_1}}} \tau(L) X_{1\tau}(\tau(L))\tau_L(L)\,dF(\theta) \\ & + \int_{\theta_{\tau}^{\overline{X_1}}}^{\theta_{\tau}^{L}} \tau(L)(X_{1\tau}(\tau(L)) + Q_{\tau}^{*}(\tau(L)))\tau_L(L)\,dF(\theta) + \int_{\theta_{\tau}^{L}}^{\overline{\theta}} (P(L,\theta)-c)\,dF(\theta) - kX_{\tau}(\tau(L))\tau_L(L)\,dF(\theta) - t \\ & - \int_{\theta_{\tau}^{L}}^{\theta_{\tau}^{X}} (P(L,\theta)-c-\tau(L))Q_{\tau}^{*}(\tau(L),\theta)\tau_L(L)\,dF(\theta) - \int_{\theta_{\tau}^{X}}^{\overline{\theta}} (P(L,\theta)-P(X,\theta))X_{\tau}(\tau(L))\,dF(\theta) \\ & + \int_{\theta_{\tau}^{L}}^{\theta_{\tau}^{X}} Q^{*}(\tau(L),\theta)\tau_L(L)\,dF(\theta) + \int_{\theta_{\tau}^{X}}^{\overline{\theta}} X(\tau(L))\tau_L(L)\,dF(\theta) + \int_{\theta^{\tau}}^{\theta_{\tau}^{\underline{X_1}}} Q^{\tau}(\tau(L),\theta)\tau_L(L)\,dF(\theta) \\ & + \int_{\theta_{\tau}^{\underline{X_1}}}^{\theta_{\tau}^{\overline{X_1}}} X_1(\tau(L))\tau_L(L)\,dF(\theta) + \int_{\theta_{\tau}^{\overline{X_1}}}^{\theta_{\tau}^{L}} (X_1(\tau(L)) + Q^{*}(\tau(L)))\tau_L(L)\,dF(\theta) = 0 \end{aligned} \tag{12}$$

We can now substitute BB_L into W_L:

$$\begin{aligned} W_L = \quad & -\tau_L(L)\left(-\int_{\theta_{\tau}^{L}}^{\theta_{\tau}^{X}} (P(L,\theta)-c-\tau(L))Q_{\tau}^{*}(\tau(L),\theta)\,dF(\theta) - \int_{\theta_{\tau}^{X}}^{\overline{\theta}} (P(L,\theta)-P(X,\theta))X_{\tau}(\tau(L))\,dF(\theta)\right) \\ & -\tau_L(L)\left(\int_{\theta_{\tau}^{L}}^{\theta_{\tau}^{X}} Q^{*}(\tau(L),\theta)\,dF(\theta) + \int_{\theta_{\tau}^{X}}^{\overline{\theta}} X(\tau(L),\theta)\,dF(\theta) + \int_{\theta^{\tau}}^{\theta_{\tau}^{\underline{X_1}}} Q^{*}(\tau(L),\theta)\,dF(\theta)\right) \\ & -\tau_L(L)\left(\int_{\theta_{\tau}^{\underline{X_1}}}^{\theta_{\tau}^{\overline{X_1}}} X_1(\tau(L))\,dF(\theta) + \int_{\theta_{\tau}^{\overline{X_1}}}^{\theta_{\tau}^{L}} (X_1(\tau(L)) + Q^{*}(\tau(L)))\,dF(\theta)\right) \end{aligned}$$

As all elements within the brackets are positive, the whole term is also positive. If we determine the sign of τ_L, we know the sign of W_L. τ_L is given by

$$\begin{aligned} \tau_L = \quad & \left(t - \int_{\theta_{\tau}^{L}}^{\overline{\theta}} (P(L,\theta)-c)\,dF(\theta)\right)\Bigg(\int_{\theta_{\tau}^{L}}^{\theta_{\tau}^{X}} Q^{*}(\tau(L),\theta)\,dF(\theta) + \int_{\theta_{\tau}^{X}}^{\overline{\theta}} X(\tau(L))\,dF(\theta) \\ & + \int_{\theta_{\tau}^{\overline{X_1}}}^{\theta_{\tau}^{L}} ((X_{1\tau}(\tau(L)) + Q_{\tau}^{*}(\tau(L)))\tau(L) + (X_1(\tau(L)) + Q^{*}(\tau(L))))\,dF(\theta) \\ & + \int_{\theta^{\tau}}^{\theta_{\tau}^{\underline{X_1}}} (Q_{\tau}^{\tau}(\tau(L),\theta)\tau(L) + Q^{\tau}(\tau(L),\theta))\,dF(\theta) + \int_{\theta_{\tau}^{\underline{X_1}}}^{\theta_{\tau}^{\overline{X_1}}} (X_{1\tau}(\tau(L))\tau(L) + X_1(\tau(L)))\,dF(\theta) \\ & - \int_{\theta_{\tau}^{L}}^{\theta_{\tau}^{X}} ((P(L,\theta)-c-\tau(L))Q_{\tau}^{*}(\tau(L),\theta))\,dF(\theta) - \int_{\theta_{\tau}^{X}}^{\overline{\theta}} (P(L,\theta)-c-\tau(L))X_{\tau}(\tau(L))\,dF(\theta)\Bigg)^{-1} \end{aligned}$$

Note that the second term is positive for $\eta \geq -1$. Hence, the sign of τ_L only depends on the first term of the equation, that is,

$$\tau_L = sign\left(t - \int_{\theta_{\tau}^{L}}^{\overline{\theta}} (P(L,\theta)-c)\,dF(\theta)\right), \tag{13}$$

which, thus, describes the size of the transmission line. In order to evaluate the size of transmission capacity relative to the generation stock, we subtract the first order condition describing generation investment (expression (9)) from expression (13).

$$\int_{\theta_{\tau}^{L}}^{\overline{\theta}} \left(P\left(\tilde{L},\theta\right)-c\right)dF(\theta) - t - \int_{\theta_{\tau}^{X}}^{\overline{\theta}} \left(P\left(\tilde{X},\theta\right)-\tau-c\right)dF(\theta) + k \gtrless 0$$

We get:
(i) $t \leq k + \left(1 - F\left(\theta_\tau^X\right)\right)\tau \Rightarrow \tau_L \leq 0$: The transmission line matches the generation capacity (corner solution).
(ii) $t > k + \left(1 - F\left(\theta_\tau^X\right)\right)\tau \Rightarrow \tau_L > 0$: The transmission line does not match the generation capacity (interior solution).
Hence, given our assumption $t < k$ on the transmission line, (i) always holds, that is, the line capacity matches the generation capacity, that is, $\tilde{X} = \tilde{L}$. Q.e.d.

E Proof of Proposition 1

This proposition compares the investment incentives under sequential market clearing with the investment incentives under simultaneous market clearing. In order to show whether under sequential market clearing investment incentives are stronger or weaker, it is sufficient to subtract the respective equilibrium conditions from each other. We start with total capacity:

E.1 Total Generation Capacity

We evaluate the difference between the first derivatives describing total capacity under sequential market clearing (expression (9)) and under simultaneous market clearing (expression (4)) evaluated at the sequential market clearing equilibrium values, $X = L$.

$$\int_{\theta_\tau^X}^{\bar{\theta}} \left(P\left(\tilde{X},\theta\right) - c\right) dF(\theta) - \int_{\theta_\tau^X}^{\bar{\theta}} \tau dF(\theta) - k$$
$$- \int_{\theta^X}^{\bar{\theta}} \left(P\left(\tilde{X},\theta\right) - c\right) dF(\theta) + (k+t) \gtreqless 0$$

Reformulating yields the following expression:

$$\int_{\underline{\theta}}^{\theta^X} \frac{Q^\tau}{\tilde{L}} dF(\theta) + \int_{\theta^X}^{\theta_\tau^X} \left(\frac{Q^\tau}{\tilde{L}} - \frac{P\left(\tilde{L},\theta\right) - c}{\tau}\right) dF(\theta)$$

The first term is clearly positive, if the second term is also positive, the whole expression is positive and hence, total capacity under sequential market clearing exceeds total capacity under simultaneous market clearing. The second term can be rewritten as

$$\frac{1}{L\tau}\int_{\theta^X}^{\theta_\tau^X}\left(\int_0^\tau Q^\tau(v,\theta)\left(\underbrace{\frac{\partial Q^\tau(v,\theta)}{\partial\tau}\frac{v}{Q^\tau(v,\theta)}}_{=\eta_\tau}+1\right)dv - \int_0^L P(v,\theta)\left(\underbrace{\frac{\partial P(v,\theta)}{\partial L}\frac{v}{P(v,\theta)}}_{=\eta_L^{-1}} + \underbrace{\frac{P(v,\theta)-c}{P(v,\theta)}}_{\epsilon[0,1]}\right)dv\right)dF(\theta).$$

This expression is positive, if $\eta \geq -1$. Q.e.d.

E.2 Baseload Generation Capacity

Again, we evaluate the difference between the first order conditions describing baseload capacity under sequential market clearing (expression (10)) and under simultaneous market clearing (expression (5)) evaluated at the equilibrium value under sequential market clearing, $\tilde{X}_1$.

$$\begin{aligned}&\int_{\theta_\tau^{\underline{X_1}}}^{\theta_\tau^{\overline{X_1}}}\left(P\left(\tilde{X}_1,\theta\right)-\tau-c_1\right)dF\left(\theta\right)+\int_{\theta_\tau^{\overline{X_1}}}^{\bar{\theta}}\left(c-c_1\right)dF\left(\theta\right)-\left(k_1-k\right)\\&-\int_{\theta^{\underline{X_1}}}^{\theta^{\overline{X_1}}}\left(P\left(\tilde{X}_1,\theta\right)-c_1\right)dF\left(\theta\right)-\int_{\theta^{\overline{X_1}}}^{\bar{\theta}}\left(c-c_1\right)dF\left(\theta\right)+\left(k_1-k\right)\quad\gtreqless\quad 0\end{aligned}$$

Reformulating yields the following expression, which is weakly negative.

$$\Leftrightarrow\underbrace{\int_{\theta^{\overline{X_1}}}^{\theta_\tau^{\overline{X_1}}}\left(P\left(\tilde{X}_1,\theta\right)-\tau-c\right)dF\left(\theta\right)}_{\leq 0}-\int_{\theta^{\underline{X_1}}}^{\theta_\tau^{\underline{X_1}}}\left(P\left(\tilde{X}_1,\theta\right)-c_1\right)dF\left(\theta\right)-\int_{\theta_\tau^{\underline{X_1}}}^{\theta^{\overline{X_1}}}\tau dF\left(\theta\right)\leq 0$$

Hence, under sequential market clearing, baseload capacity is below the level reached with simultaneous market clearing.

E.3 Transmission Capacity

From the proof in Subsection D.3 we know that for our assumption $t < k$ the transmission capacity always matches the generation capacity, that is, $\tilde{X} = \tilde{L}$. Moreover, it has also been shown in Subsection E.1 that the generation capacity with sequential market clearing exceeds the generation capacity with simultaneous market clearing, $\tilde{X} > \hat{X}$. Hence, it holds that $\tilde{L} > \hat{L}$. Q.e.d.

However, if we allow for $t > k$, $\tilde{X} = \tilde{L}$ does not necessarily hold. In order to understand how this influences our result with respect to the transmission capacity, we again evaluate the difference between the first order conditions describing transmission capacity under sequential market clearing (expression. (13)) and under simultaneous market clearing (expression (6)) evaluated at the sequential market clearing equilibrium value $\tilde{L}$.
First-best line investment is given by

$$\int_{\theta^L}^{\overline{\theta}}\left(P\left(\hat{L},\theta\right)-c\right)dF\left(\theta\right)-\left(k+t\right)=0$$

Optimal investment under sequential market clearing is given by,

$$\int_{\theta_\tau^L}^{\overline{\theta}}\left(P\left(\tilde{L},\theta\right)-c\right)dF\left(\theta\right)-t=0$$

Subtracting from each other and evaluating at the eq. values under sequential market clearing:

$$\begin{aligned}&\overbrace{\int_{\theta_\tau^L}^{\overline{\theta}}\left(P\left(\tilde{L},\theta\right)-c\right)dF\left(\theta\right)-t}^{Sequential\,Market\,Clearing}-\overbrace{\int_{\theta^L}^{\overline{\theta}}\left(P\left(\tilde{L},\theta\right)-c\right)dF\left(\theta\right)-\left(k+t\right)}^{Simultaneous\,Market\,Clearing}\\&=\underbrace{-\int_{\theta^L}^{\theta_\tau^L}\left(P\left(\tilde{L},\theta\right)-c\right)dF\left(\theta\right)}_{spot\,market\,distortion\,effect}+\underbrace{k}_{sunk\,cost\,effect}.\end{aligned}$$

If the equation above is greater than zero, it holds that $\tilde{X} > \hat{X}$. If it is smaller than zero, the opposite is true, that is $\tilde{X} < \hat{X}$. Notice that the first and the second term of the equation are independent of each other. Hence, for k large enough - everything else equal - the former holds, otherwise the latter is true.

F Generalization

F.1 Preliminary definitions

(I) **Definitions.** For tractability, we now explicitly express the peakload capacity, that is, $L - L_1 = L_0$ and $X - X_1 = X_0$ and $\Phi - \Phi_1 = \Phi_0$ with

$$\Phi_1 = \begin{cases} X_1, & if\, X_1 \leq L_1 \\ L_1, & if\, X_1 > L_1 \end{cases}, \ \Phi_0 = \begin{cases} X_0, & if\, X_0 \leq L_0 \\ L_0, & if\, X_0 > L_0 \end{cases}.$$

As with the two-node network, the actual size of the transmission lines T_1 resp. T_0 differs from their nominal size L_1 resp. L_0. The frequencies, the support and the cdf are denoted and given just as in the two-node network. However, notice that the uncertainties are independent among lines.

(II) **Spot market profits and welfare under simultaneous market clearing.** In this section we present the profits of generators and transmission owners as well as welfare for different spot markets. $W(X, X_1, L, L_1, \theta)$ denotes the economy's welfare and $\pi_i(x, x_1, l, l_1, \theta)$ the profit of a generator.

- at spot markets $\theta \epsilon \left[\underline{\theta}, \theta^{\underline{M_1}}\right]$

$$\begin{aligned} W(X_1, X_0, L_1, L_0, \theta) &= \int_0^Q (P(v, \theta) - c_1)\, dv \\ \pi(x_1, x_0, l_1, l_0, \theta) &= 0 \end{aligned}$$

- at spot markets $\theta \epsilon \left[\theta^{\underline{M_1}}, \theta^{\overline{M_1}}\right]$

$$\begin{aligned} W(X_1, X_0, L_1, L_0, \theta) &= (1 - G(X_1 - L_1)) \int_0^{X_1} (P(v, \theta) - c_1)\, dv + G(X_1 - L_1) \int_0^{L_1} (P(v, \theta) - c_1)\, dv \\ \pi(x_1, x_0, l_1, l_0, \theta) &= (1 - G(X_1 - L_1)) (P(X_1, \theta) - c_1)\, x_1 \end{aligned}$$

• at spot markets $\theta\epsilon\left[\theta^{\overline{M_1}}, \theta^{M}\right]$

$$
\begin{aligned}
W\left(X_1, X_0, L_1, L_0, \theta\right) &= \left(1-G\left(X_1-L_1\right)\right)\left(\int_0^{X_1+Q} P\left(v, \theta\right) dv-\int_0^{X_1} c_1 dv-\int_{X_1}^{X_1+Q} c dv\right) \\
&+G\left(X_1-L_1\right)\left(\int_0^{L_1+Q} P\left(v, \theta\right) dv-\int_0^{L_1} c_1 dv-\int_{L_1}^{L_1+Q} c dv\right) \\
\pi\left(x_1, x_0, l_1, l_0, \theta\right) &= \left(1-G\left(X_1-L_1\right)\right)\left(P\left(X_1+Q, \theta\right)-c_1\right) x_1
\end{aligned}
$$

• at spot markets $\theta\epsilon\left[\theta^{M}, \overline{\theta}\right]$

$$
\begin{aligned}
W\left(X_1, X_0, L_1, L_0, \theta\right) &= \left(1-G\left(X_1-L_1\right)\right)\left(1-G\left(X_0-L_0\right)\right)\left(\int_0^{X} P\left(v, \theta\right) dv-\int_0^{X_1} c_1 dv-\int_{X_1}^{X} c dv\right) \\
&+G\left(X_1-L_1\right)\left(1-G\left(X_0-L_0\right)\right)\left(\int_0^{L_1+X_0} P\left(v, \theta\right) dv-\int_0^{L_1} c_1 dv-\int_{L_1}^{L_1+X_0} c dv\right) \\
&+\left(1-G\left(X_1-L_1\right)\right) G\left(X_0-L_0\right)\left(\int_0^{X_1+L_0} P\left(v, \theta\right) dv-\int_0^{X_1} c_1 dv-\int_{X_1}^{X_1+L_0} c dv\right) \\
&+G\left(X_1-L_1\right) G\left(X_0-L_0\right)\left(\int_0^{L} P\left(v, \theta\right) dv-\int_0^{L_1} c_1 dv-\int_{L_1}^{L} c dv\right) \\
\pi\left(x_1, x_0, l_1, l_0, \theta\right) &= \left(1-G\left(X_1-L_1\right)\right)\left(1-G\left(X_0-L_0\right)\right)\left(\left(P\left(X, \theta\right)-c_1\right) x_1+\left(P\left(X, \theta\right)-c\right) x_0\right) \\
&+G\left(X_1-L_1\right)\left(1-G\left(X_0-L_0\right)\right)\left(P\left(X_1+L_0, \theta\right)-c_1\right) x_1 \\
&+\left(1-G\left(X_1-L_1\right)\right) G\left(X_0-L_0\right)\left(P\left(L_1+X_0, \theta\right)-c\right) x_0 .
\end{aligned}
$$

(III) **Spot market profits and welfare under sequential market clearing.** In this section we present the profits of generators and transmission owners as well as welfare for different spot markets. $W\left(X, X_1, L, L_1, \theta\right)$ denotes the economy's welfare and $\pi_i\left(x, x_1, l, l_1, \theta\right)$ the profit of a generator. Notice that here we only state the generation spot market profits for $X_1 \leq L_1$ and $X_0 \leq L_0$. As is shown below, this is the only relevant case.

• at spot markets $\theta\epsilon\left[\underline{\theta}, \theta_{\tau}^{M_1}\right]$

$$
\begin{aligned}
W\left(X, X_1, L, L_1 \theta\right) &= \int_0^{Q^*(\tau(L))}\left(P\left(v, \theta\right)-c_1\right) dv \\
\pi\left(x, x_1, l, \theta\right) &= 0
\end{aligned}
$$

• at spot markets $\theta\epsilon\left[\theta_{\tau}^{M_1}, \theta_{\tau}^{\overline{M_1}}\right]$

$$
\begin{aligned}
W\left(X, X_1, L, L_1, \theta\right) &= \int_0^{X_1(\tau(L))}\left(P\left(v, \theta\right)-c_1\right) dv \\
\pi\left(x, x_1, l, \theta\right) &= \left(P\left(X_1, \theta\right)-c_1\right) x_1
\end{aligned}
$$

- at spot markets $\theta\epsilon\left[\theta_{\tau}^{\overline{M_1}},\theta_{\tau}^{M}\right]$

$$\begin{aligned} W\left(X,X_1,L,L_1,\theta\right) &= \int_0^{X_1(\tau(L))+Q^*(\tau(L))} P\left(v,\theta\right)dv - \int_0^{X_1(\tau(L))} c_1 dv - \int_0^{Q^*(\tau(L))} cdv \\ \pi\left(x,x_1,l,l_1,\theta\right) &= \left(P\left(X_1+Q,\theta\right)-c_1\right)x_1 \end{aligned}$$

- at spot markets $\theta\epsilon\left[\theta_{\tau}^{M},\overline{\theta}\right]$

$$\begin{aligned} W\left(X,X_1,L,L_1,\theta\right) &= \int_0^{\phi} P\left(v,\theta\right)dv - \int_0^{X_1(\tau(L))} c_1 dv - \int_{X_1(\tau(L))}^{\phi} cdv \\ \pi\left(x,x_1,l,l_1,\theta\right) &= \left(P\left(X,\theta\right)-c_1\right)x_1 + \left(P\left(X,\theta\right)-c\right)\left(x-x_1\right) \end{aligned}$$

F.2 Proof of remark 2.

F.2.1 Socially optimal investment

(I) **Welfare and first order conditions.** The previous results enable us to derive overall welfare. It is obtained by the integral over all spot markets.

$$W\left(X_1,X_0,L_1,L_0\right)=\int_{\underline{\theta}}^{\overline{\theta}} W\left(X_1,X_0,L_1,L_0,\theta\right)dF\left(\theta\right)-k_1x_1-kx_0-tl_1-tl_0 \tag{14}$$

Note that the integrand in this expression is continuous in θ. The first derivatives are given by:

$$\begin{aligned}
W_{X_1} &= (1-G(X_1-L_1))\int_{\underline{\theta^{M_1}}}^{\overline{\theta^{M_1}}}(P(X_1,\theta)-c_1)\,dF(\theta)\\
&+(1-G(X_1-L_1))\int_{\overline{\theta^{M_1}}}^{\theta^M}(P(X_1+Q,\theta)-c_1)\,dF(\theta)\\
&+(1-G(X_1-L_1))(1-G(X_0-L_0))\int_{\theta^M}^{\bar\theta}(P(X,\theta)-c_1)\,dF(\theta)\\
&+(1-G(X_1-L_1))\,G(X_0-L_0)\int_{\theta^M}^{\bar\theta}(P(X_1+L_0,\theta)-c_1)\,dF(\theta)-k_1\\
W_{X_0} &= (1-G(X_1-L_1))(1-G(X_0-L_0))\int_{\theta^M}^{\bar\theta}(P(X,\theta)-c)\,dF(\theta)\\
&+G(X_1-L_1)(1-G(X_0-L_0))\int_{\theta^M}^{\bar\theta}(P(L_1+X_0,\theta)-c)\,dF(\theta)-k\\
W_{L_1} &= G(X_1-L_1)\int_{\underline{\theta^{M_1}}}^{\overline{\theta^{M_1}}}(P(L_1,\theta)-c_1)\,dF(\theta)+G(X_1-L_1)\int_{\overline{\theta^{M_1}}}^{\theta^M}(P(L_1+Q,\theta)-c_1)\,dF(\theta)\\
&+G(X_1-L_1)(1-G(X_0-L_0))\int_{\theta^M}^{\bar\theta}(P(L_1+X_0,\theta)-c_1)\,dF(\theta)\\
&+G(X_1-L_1)\,G(X_0-L_0)\int_{\theta^M}^{\bar\theta}(P(L,\theta)-c_1)\,dF(\theta)-t\\
W_{L_0} &= (1-G(X_1-L_1))\,G(X_0-L_0)\int_{\theta^M}^{\bar\theta}(P(X_1+L_0,\theta)-c)\,dF(\theta)\\
&+G(X_1-L_1)\,G(X_0-L_0)\int_{\theta^M}^{\bar\theta}(P(L,\theta)-c)\,dF(\theta)-t
\end{aligned}$$

(II) **Equilibrium.** In equilibrium, the first derivatives have to be equal to zero. Hence, transmission and generation capacity have to be of the equal capacity:

$$X_1^*=L_1^* \quad and \quad X_0^*=L_0^*$$

Using $X-X_1=X_0$ and $L-L_1=L_0$, this is

$$X^* \;:\; \int_{\theta^X}^{\bar\theta}(P(X^*,\theta)-c)\,dF(\theta)-(k+t)=0 \tag{15}$$

$$X_1^* \;:\; \int_{\underline{\theta^{X_1}}}^{\overline{\theta^{X_1}}}(P(X_1^*,\theta)-c_1)\,dF(\theta)+\int_{\overline{\theta^{X_1}}}^{\bar\theta}(c-c_1)\,dF(\theta)-(k_1-k)=0 \tag{16}$$

(III) **Uniqueness.** As in equilibrium $X^*=L^*$ and $X_1^*=L_1^*$ have to hold, it is sufficient to check the second order conditions only for the joint equilibrium conditions from (II) with respect to X

and X_1. The second derivatives are given by

$$\begin{aligned} W_{XX}\left(X,X_1,L,L_1\theta\right)+W_{LL}\left(X,X_1,L,L_1\theta\right) &= \int_{\theta^X}^{\overline{\theta}} P_q\left(X,\theta\right)dF\left(\theta\right)<0 \\ W_{X_1X_1}\left(X,X_1,L,\theta\right) &= \int_{\theta^{\underline{X_1}}}^{\theta^{\overline{X_1}}} P_q\left(X_1,\theta\right)+\int_{\theta^{\overline{X_1}}}^{\theta^X} P_q\left(X_1+Q,\theta\right)<0 \\ W_{XX_1}\left(X,X_1,L,\theta\right) &= 0 \end{aligned}$$

As is easy to see, the absolute value of the cross derivatives is smaller than the absolute value of any of the second derivatives

$$\mid W_{xx}\left(X,X_1,L\right)\mid,\mid W_{x_1x_1}\left(X,X_1,L\right)\mid>\mid W_{xx_1}\left(X,X_1,L\right)\mid$$

Hence, the product of the cross derivatives is smaller than the product of the second derivatives:

$$\pi_{xx}\left(X,X_1,L\right)\cdot\pi_{x_1x_1}\left(X,X_1,L\right)>0$$

That is, the first order conditions describe a unique equilibrium.

F.2.2 Investment under simultaneous market clearing

(I) **Profits and first order conditions.** The previous results enable us to derive overall profits and welfare. These are obtained by the integral over all spot markets and given by

$$\pi_i\left(x_1,x_0,l_1,l_0\right)=\int_{\underline{\theta}}^{\overline{\theta}}\pi_i\left(x_1,x_0,l_1,l_0,\theta\right)dF\left(\theta\right)-k_1x_1-kx_0 \tag{17}$$

Note that the integrand in this expression is continuous in θ. The first derivatives for generation investment are given by:

$$\begin{aligned} \pi_{X_1} =\;& \left(1-G\left(X_1-L_1\right)\right)\int_{\theta^{\underline{M_1}}}^{\theta^{\overline{M_1}}}\left(P\left(X_1,\theta\right)-c_1\right)dF\left(\theta\right)+\left(1-G\left(X_1-L_1\right)\right)\int_{\theta^{\overline{M_1}}}^{\theta^M}\left(P\left(X_1+Q,\theta\right)-c_1\right)dF\left(\theta\right) \\ &+\left(1-G\left(X_1-L_1\right)\right)\left(1-G\left(X_0-L_0\right)\right)\int_{\theta^M}^{\overline{\theta}}\left(P\left(X,\theta\right)-c_1\right)dF\left(\theta\right) \\ &+\left(1-G\left(X_1-L_1\right)\right)G\left(X_0-L_0\right)\int_{\theta^M}^{\overline{\theta}}\left(P\left(X_1+L_0,\theta\right)-c_1\right)dF\left(\theta\right)-k_1 \\ \pi_{X_0} =\;& \left(1-G\left(X_0-L_0\right)\right)\left(1-G\left(X_1-L_1\right)\right)\int_{\theta^M}^{\overline{\theta}}\left(P\left(X,\theta\right)-c\right)dF\left(\theta\right) \\ &+\left(1-G\left(X_0-L_0\right)\right)G\left(X_1-L_1\right)\int_{\theta^M}^{\overline{\theta}}\left(P\left(L_1+X_0,\theta\right)-c\right)dF\left(\theta\right) \\ &+G\left(X_0-L_0\right)\left(1-G\left(X_1-L_1\right)\right)\int_{\theta^M}^{\overline{\theta}}\left(P\left(X_1+L_0,\theta\right)-c\right)dF\left(\theta\right)-k \end{aligned}$$

The first order conditions for the socially optimal transmission line investment are identical to those in Section F.2.1.

(II) **Equilibrium.** The equilibrium equates the first derivatives to zero. Hence, in equilibrium transmission lines and generation have to be of the same capacity:

$$\hat{X}_1 = \hat{L}_1 \quad and \quad \hat{X}_0 = \hat{L}_0$$

This is

$$\begin{aligned}
\pi_{X_1} &= \left(1 - G\left(\hat{X}_1 - \hat{L}_1\right)\right) \int_{\theta^{\underline{M_1}}}^{\theta^{\overline{M_1}}} \left(P\left(\hat{X}_1, \theta\right) - c_B\right) dF(\theta) \\
&\quad + \left(1 - G\left(\hat{X}_1 - \hat{L}_1\right)\right) \int_{\theta^{\overline{M_1}}}^{\theta^M} \left(P\left(\hat{X}_1 + Q, \theta\right) - c_B\right) dF(\theta) \\
&\quad + \left(1 - G\left(\hat{X}_1 - \hat{L}_1\right)\right) \int_{\theta^M}^{\overline{\theta}} \left(P\left(\hat{X}, \theta\right) - c_1\right) dF(\theta) - k_1 = 0
\end{aligned} \tag{18}$$

$$\pi_{X_0} = (1 - G(X_0 - L_0)) \int_{\theta^M}^{\overline{\theta}} \left(P\left(\hat{X}, \theta\right) - c_P\right) dF(\theta) - k = 0 \tag{19}$$

$$\begin{aligned}
W_{L_1} &= G\left(\hat{X}_1 - \hat{L}_1\right) \int_{\theta^{\underline{M_1}}}^{\theta^{\overline{M_1}}} \left(P\left(\hat{X}_1, \theta\right) - c_1\right) dF(\theta) + G\left(\hat{X}_1 - \hat{L}_1\right) \int_{\theta^{\overline{M_1}}}^{\theta^M} (c - c_1)\, dF(\theta) \\
&\quad + G\left(\hat{X}_1 - \hat{L}_1\right) \int_{\theta^M}^{\overline{\theta}} \left(P\left(\hat{X}, \theta\right) - c_1\right) dF(\theta) - t
\end{aligned} \tag{20}$$

$$W_{L_0} = G\left(\hat{X}_0 - \hat{L}_0\right) \int_{\theta^M}^{\overline{\theta}} \left(P\left(\hat{L}, \theta\right) - c\right) dF(\theta) - t = 0 \tag{21}$$

The sum of conditions (18) and (20) is identical to condition (16) and the sum of conditions (19) and (21) is identical to condition (15). Hence, under simultaneous market clearing the socially optimal investment outcome emerges. Q.e.d.

(III) **Uniqueness.** Conditions (18), (20), (19) and (21) are identical to the conditions describing the socially optimal investment (eq. (16) and (15)). As we have shown, the later constitutes a unique equilibrium. Hence, also the first order conditions (18), (19), (20) and (21) do. Q.e.d.

F.3 Proof of Proposition 2.

The generation profit function, the welfare function and the budget balancing equation are identical to the respective functions in the two-node case (eq. (3), (11) and (7)). Hence, given our assumption $t < k$ on the transmission line, total transmission capacity always matches total generation capacity, $\tilde{X} = \tilde{L}$. Moreover, the transmission capacity at any line never exceeds the generation capacity. This implies that $\tilde{L}_1 = \tilde{X}_1$ and $\tilde{L}_0 = \tilde{X}_0$. Hence, the results from the two-node case also apply here. Q.e.d.