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Abstract

Adequately designed prices are essential to achieve efficient coordination between the electricity network and market participants. However, consumer prices comprise several, possibly distorting price components. In an analytical model, we examine different regulatory settings, consisting of alternative spot market pricing schemes and network tariff designs in a dynamic context. While a setting with zonal pricing and fixed network tariffs achieves the highest welfare, a deviation of either the pricing scheme or the network tariff design leads to inefficiencies. However, we show that two inefficiently designed price components can be better than one, especially if network tariffs correct for the static inefficiency of the pricing scheme. Besides the network tariff design, network operators must pay attention to the allocation of network costs. It affects spatial price signals and, therefore, the dynamic allocation of investment decisions. Considering these decisions in a dynamic framework increases the requirements for the configuration of network tariffs, especially with volume-based network tariffs.

Keywords: Network tariffs, network regulation, market design, pricing schemes, dynamic consistency, spatial investment incentives

JEL classification: D47, D61, L51, L94, Q41

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1. Introduction

The transition towards a decarbonized energy system requires investments in new electricity consumption technologies, like power-to-gas facilities or electric heating systems. In liberalized electricity systems, investment and operation decisions are private and based on price signals. Therefore, adequately designed prices are of great importance to efficiently coordinate the network and decisions of supply and demand. Increasingly decentralized investments and rising network costs make spatial price signals even more relevant. In many electricity systems, however, prices for consumers do not include spatial signals, and in most cases, they contain several price components that are not necessarily aligned. While the demand-side has traditionally been perceived as price-inelastic, with new demand-side technologies entering the system, consumers can participate more actively in electricity markets. Therefore, misaligned price signals can have an increasingly negative impact on welfare and the system's efficiency. The adequacy of price signals depends on the design of several components, including the spot market pricing scheme and regulatory price components, like network tariffs. In many countries, network tariffs account for a significant part of the consumer price. In addition to the sum of price components that directly affect the consumers' decision-making, the individual price components can interact with each other. These interactions depend on the design of the individual components.

In this paper, we analyze the interactions of price components by combining different spot market pricing schemes and network tariff designs. We derive static and dynamic effects within each regulatory setting and analyze how regulatory changes impact efficiency by ranking the regulatory settings in terms of overall welfare. The analysis particularly accounts for network tariffs' economic efficiency, including their function to recover network costs for the network operator and their ability to ensure a dynamically consistent allocation of demand investments.

We develop a theoretical two-node model, including a spot market and the network tariff setting of a transmission system operator (TSO).[1] The TSO decides on welfare optimal network tariffs that must recover the network costs. She anticipates the dynamic effects of price signals and optimizes

[1] In the following, we refer to the transmission network only. However, due to the stylized representation of network constraints, this does not necessarily exclude our model's application in the context of distribution networks.

network tariffs such that upcoming demand investments are efficiently allocated. Subsequently, the spot market clearing follows, if necessary, accompanied by congestion management measures. We apply the model in four different regulatory settings - the combination of two spot market pricing schemes and two network tariff designs. As pricing schemes, we consider zonal and uniform pricing because they represent two contrasting approaches to incorporate network constraints in the market clearing.[2] As network tariff designs, we consider fixed and volume-based network tariffs. Economic theory on efficient pricing suggests fixed network tariffs as they do not distort market price signals (c.f. Pérez-Arriaga and Smeers, 2003). In contrast, volume-based tariffs increase the per-unit price for consumers. If consumers react to prices, volume-based network tariffs induce a deadweight loss. Ramsey-Boiteux prices minimize this deadweight-loss and constitute the least-distorting volume-based network tariffs (c.f. Wilson, 1993).

The regulatory setting with zonal pricing and fixed network tariffs achieves the highest welfare. Without reducing the static welfare, the TSO can ensure a dynamically consistent allocation of demand investments by restricting the feasible cost allocation between the two nodes. In the regulatory setting with uniform pricing and fixed network tariffs, the TSO also achieves a dynamically consistent allocation of demand investments without reducing the static welfare. However, the cost allocation is further restricted, as the network tariffs are the only possibility for spatial price signals. Additionally, the introduction of uniform pricing leads to inefficiency from congestion management, as we assume a cost-based redispatch mechanism of generators. With volume-based network tariffs, the inefficiency from the congestion management reduces, if the TSO includes a correction term into the network tariff, which imitates zonal prices. Under both pricing schemes, volume-based network tariffs induce a deadweight loss as they increase per-unit prices and, therefore, impact the spot market outcome. In contrast to fixed network tariffs, optimal volume-based network tariffs can lead to an additional loss in static welfare when considering a dynamically consistent allocation of demand investments.

[2] We use the term zonal pricing as a general approach for spatially differentiated prices within one regulated region. This definition includes all pricing schemes in which the spot market sends locational price signals to the market participants. The concept of zonal pricing preserves the possibility that several nodes of a network constitute a zone, while prices may differ between the zones of one region. Within our two-node model, nodal or zonal prices are equivalent.

Comparing the four regulatory settings shows that deviating from the regulatory setting of zonal pricing and fixed network tariffs leads to inefficiencies. Under uniform pricing, additional costs occur due to congestion management, and the use of volume-based network tariffs results in a deadweight loss due to price distortion. If there is only one source of inefficiency, welfare increases by adjusting the respective price component, i.e., changing either to fixed network tariffs or zonal pricing. However, suppose both sources of inefficiency are present. In that case, i.e., the combination of uniform pricing and volume-based network tariffs, an adjustment of only one aspect can have unintended effects on overall welfare. If optimal volume-based network tariffs structurally reduce congestion management costs, switching to fixed network tariffs does not necessarily increase market efficiency. This result is important considering that current electricity systems often use a combination of uniform pricing and mainly volume-based network tariffs. Hence, we demonstrate the importance of addressing the interactions between price components when changing the regulatory setting.

This paper contributes to the broader literature on network cost recovery, focusing on the interactions with different spot market pricing schemes in a dynamic context. Electricity networks constitute a natural monopoly and typically face large, fixed network costs. Thus, competitive pricing at short-run marginal costs does not generate enough revenue to cover total costs (c.f. Pérez-Arriaga et al., 1995; Joskow, 2007). Therefore, cost recovery is necessary independently of the spot market pricing scheme and requires an appropriate network tariff design (c.f. Brunekreeft et al., 2005). Borenstein (2016) comprehensively discusses the aspect of fixed cost recovery in natural monopolies and the economic principles of tariff setting in electricity markets. Furthermore, Batlle et al. (2020) and Schittekatte (2020) conceptually discuss options for residual cost allocation, with a special focus on residential consumers and distributional effects of network tariffs. This strand of literature is expanded by empirical studies on the distributional effects, e.g., by Burger et al. (2020) and Ansarin et al. (2020), as well as numerical simulation models, that analyze the effects of different network tariffs on different consumer groups, e.g., Fridgen et al. (2018) and Richstein and Hosseinioun (2020).

In a dynamic context, the demand-side has received relatively little attention so far, as consumers' investment decisions have long been considered not being influenced by electricity price signals.

In their recent work on prosumers, Schittekatte et al. (2018) and Schittekatte and Meeus (2020) analyze the effect of network tariffs on consumers' investment incentives and the installation of residential PV. Gautier et al. (2020) contribute to the discussion on investment incentives by taking the presence of heterogeneous prosumers into account and Castro and Callaway (2020) simulate the impact of different network tariffs on demand's investment decisions in a numerical model. Though, these analyses do not consider the spatial dimension and locational choices. While Ambrosius et al. (2018) do analyze spatial demand investments under different spot market pricing schemes, they do not consider multiple network tariff designs. In comparison, the literature acknowledging the spatial dimension and the impact of network tariffs on location-based price signals is currently limited to the supply side. Tangerås and Wolak (2019) analytically show how locational marginal network tariffs can be designed to incentivize efficient supply-side investments. Bertsch et al. (2016) analyze different pricing schemes in a dynamic numerical framework. They consider the interactions of network tariffs (specifically a g-component) and the pricing scheme. Similarly, Grimm et al. (2019) apply regionally differentiated network tariffs under different pricing schemes for the German electricity market. Ruderer and Zöttl (2018) account for the interaction of congestion management methods and network tariffs by examining the impact of volume- and capacity-based network tariffs on generators' investment decision in an analytical model. The importance of efficient cost recovery mechanisms is also highlighted by Chao and Wilson (2020). In a numerical model they find volume-based Ramsey-Boiteux tariffs to be close to the social optimum.

To the best of our knowledge, the paper at hand is the first, which explicitly considers different network tariff designs and pricing schemes in a consistent dynamic framework to analyze the effect on spatial demand-side decisions. Although each of these topics has been studied extensively from an isolated perspective, integrated approaches are relatively scarce. Borenstein and Bushnell (2018) empirically analyze the interaction of network tariffs and the pricing of externalities in the US. The authors show that if prices are affected by more than one distortion, the effects can level each other out. We contribute to the discussion by developing an analytical framework in which we provide insights into the interaction of the two price components, their potential inefficiencies and the requirements for a dynamically consistent allocation of demand-side investments.

The remainder of this paper is structured as follows: Section 2 introduces our model set-up, and section 3 analyzes the optimal network tariffs under different pricing schemes in a dynamic context. Section 4 examines the effects of the regulatory settings on overall welfare. Section 5 discusses political implications and summarizes concluding remarks.

2. The model framework

This section introduces the basic model setup to analyze different pricing schemes and network tariff designs in the presence of a congested transmission network. We consider a two-node model with two nodes called *north* and *south* denoted by $i \in \{n, s\}$ with respective generation technologies with constant marginal costs c_i. Further, we assume that the generation technology in the north is strictly cheaper, i.e., $c_n < c_s$. Both technologies have an unrestricted generation capacity. Further, we assume perfect competition in both nodes. Thus producer surplus is equal to zero in all regulatory settings. The aggregated market demand in each node is denoted by $D_i(p_i)$, which is decreasing in price, i.e., ${}^{\partial D_i(p_i)}/_{\partial p_i} < 0 \; \forall \; i$. We assume a positive number of ω_i identical consumers in each node. The total number of consumers is therefore given by $\Omega = \omega_n + \omega_s$.

Electricity generation q_i in both nodes needs to cover total demand, i.e., $\sum_i q_i = \sum_i D_i(p_i)$. Further, the two nodes are connected by a transmission line, with power flows l and a limited capacity of $\overline{L}$, illustrated in figure 1. We focus on congested networks and hence demand exceeds the limited transmission line capacity, i.e., $\overline{L} \leq D_i(p_i) \; \forall \; i$. Since we assume that generation costs are lower in the north, electricity flows from north to south. The transmission system operator (TSO) is responsible for the physical feasibility of the market outcome, which, if necessary, also comprises congestion management.

In our analysis, we consider two pricing schemes - zonal and uniform pricing that differ regarding their congestion management. Under zonal pricing, the spot market clearing simultaneously considers network restrictions, while under uniform pricing, ex-post congestion management of the TSO is necessary. After the spot market clearing, the TSO performs a redispatch of supplied quantities q_i until the transmission constraint $\overline{L}$ is fulfilled.

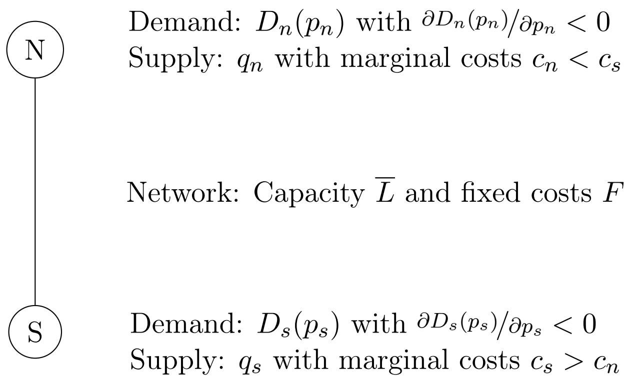

Figure 1: The two-node model.

We assume a redispatch mechanism with incomplete participation. That means, the TSO considers only producers for redispatch, while the demand-side is excluded.[3] This reflects the common practice in many electricity systems and is, in particular, due to the complexity of remunerating the demand for a redispatch measure. With a cost-based redispatch, the TSO compensates generators outside the spot market based on their marginal costs.[4]

Additionally, the operation of the transmission network is associated with fixed costs of $F \in]0, \infty[$. We assume that the fixed costs are smaller than the consumer surplus given the generation costs in each node, i.e., $F \leq \int_{c_i}^{\infty} D_i(z)dz \ \forall \ i$. This assumption ensures the participation constraint of consumers in all settings. Fixed network costs cannot be attributed to individual network users. Therefore, the principle of cost causality cannot be applied to recover these costs. The TSO's total network costs C^{TSO} contain the fixed costs F as well as potential congestion rents. Depending on the pricing scheme, congestion rents can be either positive or negative. We introduce the TSO as a benevolent agent who recovers her costs by charging network tariffs. We consider two different network tariff designs: a volume-based tariff $\boldsymbol{\tau} := (\tau_n, \tau_s)$, and a fixed network tariff $\boldsymbol{f} := (f_n, f_s)$. Volume-based network tariffs can be interpreted as an additional demand tax that directly influences the demand decision on the spot market. Fixed network tariffs can be interpreted as an access charge for being connected to the network. These tariffs constitute two extreme cases

[3]Noteworthy, under the assumption of full participation, uniform pricing with redispatch achieves the welfare optimal result (Bjorndal et al., 2013).

[4]Other congestion management methods are comprehensively discussed in DeVries and Hakvoort (2002), Holmberg and Lazarczyk (2015) and Weibelzahl (2017).

for network cost recovery. We do not apply general non-linear tariffs, e.g., multi-part tariffs. In both cases, we assume that only consumers pay network tariffs, as is the case in many electricity systems in practice. The TSO can differentiate between consumers in the north and south but cannot distinguish between consumers within one node. Consequently, network tariffs can vary between the two nodes, but not between consumers within a node.

For the network tariff setting, the TSO wants to ensure a dynamically consistent allocation of demand investments. By definition, new consumers choose the location of their investment depending on the prices in each node. We define a pricing schedule P_i^I that includes two price components: the payments at the spot market for each unit demanded and the network tariff payments. The pricing schedule is given by $P_i^I = p_i\overline{D} + f_i$, where $\overline{D}$ is a fixed additional demand for new consumers.[5] If volume-based network tariffs are applied, the per unit price p_i also includes the network tariff τ_i. The TSO aims at achieving a dynamically consistent allocation of demand investments. From a welfare perspective, dynamic consistency is achieved if the new demand investments are in line with the welfare-maximizing result in future periods. As we consider a congested network with lower generation costs in the north, consumers should place new demand investments into the north. The demand invests in the north, if and only if, the pricing schedule is lower in the north compared to the south, i.e., iff $P_n^I \leq P_s^I$, which is:

$$p_n(\boldsymbol{c}, \boldsymbol{\tau}) \cdot \overline{D} + f_n \leq p_s(\boldsymbol{c}, \boldsymbol{\tau}) \cdot \overline{D} + f_s \tag{1}$$

The TSO anticipates the rationale of the demand's investment decision and, therefore, accounts for the pricing schedule (1) when setting the network tariffs. The structure of this constraint holds in each setting and only the spot market price and the network tariff may change depending on the regulatory setting.[6]

[5] By assuming a price-inelastic demand, we ignore quantity effects, which additionally restrict the optimal solution, but do not change our main results.

[6] We simplify the investment decision by only considering the costs in both nodes and add the investment decision to the pricing problem of the TSO. If the investment decision is modeled endogenously in a sequential setting, i.e., by maximizing the consumer surplus of the invested demand, the rationale slightly differs between the settings, but our main results do not change.

3. The interactions of network tariffs and pricing schemes considering dynamic consistency

We analyze the interactions between the different combinations of pricing schemes and network tariff designs and their effect on a dynamically consistent allocation of demand investments. The model set-up consists of two steps.

At first, the benevolent TSO introduces a vector of network tariffs for the current time period that can either be fixed ($\boldsymbol{f}$) or volume-based ($\boldsymbol{\tau}$). The TSO has perfect foresight and anticipates the impact of network tariffs on the spot market outcome and possible network congestion while ensuring the dynamic consistency of the pricing schedule.[7]

Second, the spot market clearing takes place, which depends on the pricing schemes. Under zonal pricing, the spot market clears with a cost-minimal dispatch considering the transmission constraint. The solution is equal to the optimal dispatch of a social planner, as we show in Appendix A. Production is equal to $q_n^* = D_n(p_n) + \overline{L}$ and $q_s^* = D_s(p_s) - \overline{L}$. Prices differ among nodes and reflect marginal costs of generation, with $p_n^* = c_n$ and $p_s^* = c_s$. The spot market clearing under zonal pricing yields a positive congestion rent $(c_s - c_n)\overline{L}$. The TSO anticipates this rent and offsets fixed costs F with it. Under uniform pricing, both nodes belong to the same bidding zone. In contrast to zonal pricing, both nodes trade irrespective of network constraints. Consequently, the generation in the north is dispatched to fully cover the demand in both nodes at marginal costs of c_n. The resulting spot market prices are $p_n^* = p_s^* = c_n$.[8] The spot market clearing requires a production of $q_n = D_n(c_n) + D_s(c_n)$, which is technically not feasible as it requires the producer at node n to export more than $\overline{L}$. The TSO is responsible for ensuring the system's physical feasibility by conducting congestion management measures. To do so, the TSO performs a redispatch of suppliers. The TSO instructs the producer at node n to reduce generation to $q_n = D_n(c_n) + \overline{L}$ and instructs the producer at node s to increase generation to $q_s = D_s(c_n) - \overline{L}$. The TSO compensates the producers outside the spot market for redispatching their generation. This leads to additional

[7] The assumption regarding the TSO's benevolence is critical for the formulation of the optimization problem. Otherwise, the TSO would only consider her budget and neglect the impact on consumer surplus or dynamic consistency.

[8] With volume-based network tariffs, the per-unit price in each node also includes τ_n and τ_s, respectively, and hence, in sum p_i may differ between both nodes. However, the spot market price component is the same, regardless of the network tariff design.

costs of $(c_s - c_n)(D_s(p_s^*) - \overline{L})$. In the following, we use these spot market results to determine the optimal network tariffs.

3.1. Fixed network tariffs under zonal pricing

The TSO maximizes welfare by setting the fixed network tariffs under zonal pricing (2a). The optimization is subject to the budget constraint (2b) to ensure full network cost recovery. Due to the positive congestion rent under zonal pricing, the TSO has to recover the following costs $C_{ZP,f}^{TSO} = F - (c_s - c_n)\overline{L}$. Further, the TSO anticipates the impact of network tariffs on the dynamic allocation of demand investments. Therefore, the optimization is additionally restricted by (2c).

$$\max_{\boldsymbol{f}} W_{ZP,f}(\boldsymbol{p}^*, \boldsymbol{f}) = \int_{p_n^*=c_n}^{\infty} D_n(z)\,\mathrm{d}z + \int_{p_s^*=c_s}^{\infty} D_s(z)\,\mathrm{d}z - F + (c_s - c_n)\overline{L} \tag{2a}$$

$$s.t. \quad \sum_i \omega_i f_i - F + (c_s - c_n)\overline{L} = 0 \tag{2b}$$

$$c_n\overline{D} + f_n \leq c_s\overline{D} + f_s \tag{2c}$$

The fixed network tariffs do not impact the welfare function and the TSO only has to ensure, that the constraints (2b) and (2c) hold. See Appendix B for a proof and the derivation of possible solutions for the optimization problem (2a-2c). As consumers are homogeneous and fixed costs do not exceed consumer surplus in each node, fixed network tariffs cannot exceed the individual consumer surplus. Hence, the participation constraint holds for each consumer. Thereby, fixed network tariffs do not change the cost-minimal dispatch of supply and demand and thus, do not distort welfare. This is a well-known result from the literature on fixed cost recovery in network industries (e.g. Wilson, 1993; Joskow, 2007; Borenstein, 2016). Within the boundaries of constraints (2b) and (2c), the TSO can allocate the costs freely among the nodes.[9] Allocating network costs equally among consumers in all nodes would be a practical solution that ensures a dynamically consistent allocation of demand investments. In practice, this approach is often called *horizontal cost allocation*. Such a simple allocation rule would ensure that network tariffs do not distort spatial price signal from the spot market while fully recovering the fixed network costs.

[9]We ignore income and distribution effects in our model. Considering these effects may change the socially desirable cost allocation, e.g. if additional restrictions are included in the optimization problem. See for example Batlle et al. (2020) for a discussion on this topic and a proposed alternative to fixed network tariffs.

3.2. Fixed network tariffs under uniform pricing

Under uniform pricing, the optimization problem of the TSO changes to (3a-3c). First, the spot market prices differ from zonal pricing, and second, the budget constraint of the TSO (3b) changes. Since redispatch comes with additional costs for the TSO, she has to recover total costs of $C^{TSO}_{UP,f} = F + (c_s - c_n)(D_s(p^*_s) - \overline{L})$. Again, the TSO ensures the dynamic consistency for the allocation of future demand investments (3c). As the per-unit spot price is equal in both nodes, the additional demand quantity $\overline{D}$ cancels out.

$$\max_{\boldsymbol{f}} W_{UP,f}(\boldsymbol{p}^*, \boldsymbol{f}) = \int_{p^*_n=c_n}^{\infty} D_n(z)\,\mathrm{d}z + \int_{p^*_s=c_n}^{\infty} D_s(z)\,\mathrm{d}z - F - \big[(c_s - c_n)(D_s(p^*_s) - \overline{L})\big] \tag{3a}$$

$$s.t. \quad \sum_i \omega_i f_i - F - \big[(c_s - c_n)(D_s(p^*_s) - \overline{L})\big] = 0 \tag{3b}$$

$$f_n \leq f_s \tag{3c}$$

Proposition 1. *With fixed network tariffs and homogeneous consumers, the TSO can ensure dynamic consistency without impacting static welfare by restricting the feasible cost allocation between the two nodes. Under uniform pricing, the cost allocation between the nodes is further restricted compared to zonal pricing.*

Again, the fixed network tariffs do not affect welfare and the TSO only has to ensure that the constraints (3b) and (3c) are met.[10] However, under uniform pricing, the solution to the optimization problem is more constrained by the dynamic consistency condition compared to the setting under zonal pricing. The boundary on network tariffs changes from $c_n\overline{D} + f^*_n \leq c_s\overline{D} + f^*_s$ under zonal pricing to $f^*_n \leq f^*_s$ under uniform pricing. Thus, to ensure a dynamically consistent allocation, the TSO has to choose network tariffs that compensate for the spot market's missing spatial price signals under uniform pricing.

3.3. Volume-based network tariffs under zonal pricing

As in section 3.1, spot market prices differ between the nodes and reflect the respective marginal costs. However, unlike fixed network tariffs, volume-based network tariffs constitute a levy on consumption and directly influence the demand decision at the spot market. The total price,

[10]It is straightforward to see that the solution of this optimization resembles to the solution of the previous chapter, which is depicted in Appendix B.

that consumers pay per unit, is the marginal costs of generation c_i plus the network tariff τ_i, i.e. $p_i = c_i + \tau_i$. The demand-side reduces demanded quantities accordingly.

The TSO maximizes welfare by choosing the optimal vector of volume-based network tariffs (4a-4c). The optimization is subject to the TSO's break-even constraint (4b).[11] The TSO accounts for the positive congestion rent from zonal pricing, and consequently, recovers costs of $C_{ZP,\tau}^{TSO} = F - (c_s - c_n)\overline{L}$. Additionally, the optimization is restricted by the dynamic consistency constraint (4c). With volume-based network tariffs, the constraint is independent of the fixed additional demand of new consumers ($\overline{D}$) and only depends on the per unit price $p_i(c_i, \tau_i)$.

$$\max_{\boldsymbol{\tau}} W_{ZP,\boldsymbol{\tau}}(\boldsymbol{p}^*(\boldsymbol{\tau})) = \int_{p_n^*=c_n+\tau_n}^{\infty} D_n(z)\,\mathrm{d}z + \int_{p_s^*=c_s+\tau_s}^{\infty} D_s(z)\,\mathrm{d}z + \sum_i \tau_i D_i(p_i^*) - F + (c_s - c_n)\overline{L} \tag{4a}$$

$$s.t. \quad \sum_i \tau_i D_i(p_i^*) - F + (c_s - c_n)\overline{L} = 0 \quad \longrightarrow \quad \lambda \tag{4b}$$

$$c_n + \tau_n \leq c_s + \tau_s \quad \longrightarrow \quad \mu \tag{4c}$$

Proposition 2. *If the dynamic consistency constraint is binding, the network tariffs deviate from the optimal static volume-based network tariffs. In this case and under the assumption of constant marginal costs, a dynamically consistent allocation of demand investments lowers static welfare since consumer surplus in the north increases less than consumer surplus in the south decreases.*

To solve the TSO's optimization problem we derive the first-order condition of the Lagrangian $\partial L / \partial \tau_i$. Rearranging for τ_n^* and τ_s^* yields

$$\tau_n^* = \frac{\lambda}{1+\lambda} \cdot \frac{D_n(c_n + \tau_n^*)}{-\partial D_n(c_n+\tau_n^*)/\partial \tau_n^*} - \frac{\mu}{1+\lambda} \cdot \frac{1}{-\partial D_n(c_n+\tau_n^*)/\partial \tau_n^*} \tag{5}$$

and

$$\tau_s^* = \frac{\lambda}{1+\lambda} \cdot \frac{D_s(c_s + \tau_s^*)}{-\partial D_s(c_s+\tau_s^*)/\partial \tau_s^*} + \frac{\mu}{1+\lambda} \cdot \frac{1}{-\partial D_s(c_s+\tau_s^*)/\partial \tau_s^*} \tag{6}$$

[11] Note that the TSO is unbundled. Unlike the case of a classical, vertically integrated natural monopoly, the TSO does not increase the spot market price to recover her fixed cost but introduces a separate network tariff. The difference is that network tariffs are a payment from consumers to the TSO. Therefore, the congestion rent $(c_s - c_n)\overline{L}$ and producer profits are not affected by the network tariffs and remain constant.

We distinguish between two cases:[12] First, assume that the constraint for dynamic consistency (4c) is non-binding and $\mu = 0$. Then, the optimal network tariff in both nodes is equal to:

$$\tau_i^* = \frac{\lambda}{\lambda + 1} \cdot \frac{D_i(c_i + \tau_i^*)}{-\partial D_i(c_i+\tau_i^*)/\partial \tau_i^*} \tag{7}$$

In this case, the optimal network tariff (7) can be interpreted as a modified version of the Ramsey-Boiteux inverse elasticity rule (see Appendix C.1). A high variation in demand in response to a variation in price leads to lower network tariffs. To solve for the optimal network tariffs, we define the *quasi-elasticity* ρ_i, insert it into (7) and equate for both nodes. We obtain the following relation:

$$\frac{\tau_n^*}{\tau_s^*} = \frac{\rho_s(\tau_s^*)}{\rho_n(\tau_n^*)} \quad \text{with} \quad \rho_i(\tau_i^*) = -\frac{\partial D_i(c_i+\tau_i^*)/\partial \tau_i}{D_i(c_i + \tau_i^*)} \tag{8}$$

The relationship between the network tariffs in the two nodes corresponds to the relationship between the quasi-elasticities. By using the relationship from (8) and the budget constraint of the TSO (4b), we solve for the optimal network tariff in the south:

$$\tau_s^* = \frac{F - (c_s - c_n)\overline{L}}{\frac{\rho_s(\tau_s^*)}{\rho_n(\tau_n^*)} D_n(c_n + \tau_n^*) + D_s(c_s + \tau_s^*)} \tag{9}$$

The result can be derived analogously for τ_n^*. Similar to the Ramsey-Boiteux inverse elasticity rule, we see that when the ratio of the quasi-elasticities between the south and the north decreases, i.e., when the price sensitivity of the north increases compared to the south, demand in the south covers a higher share of the residual network costs and vice versa. In this case, the condition for dynamically consistent allocation is already met without any further adjustments to the network tariffs. The optimal static volume-based network tariffs thus provide dynamic consistency by themselves.

Second, assume that (4c) is binding and $\mu > 0$. This is the case if the optimal static network tariffs reverse the ratio of price schedules between the two nodes so that the north would become more expensive than the south. This depends on the ratio of the demand functions, particularly the quasi-elasticities, in the two nodes (see (8)). We denote the resulting network tariffs with $\hat{\tau}_i$.[13] As $\mu > 0$ it follows from (5) and (6) that $\hat{\tau}_i$ deviate from τ_i^*. In the north, the optimal volume-based

[12] There exists a third case where $\mu = 0$ and the constraint is binding. This case leads to the same solution as our first case.

[13] In Appendix C.2, we solve for the optimal network tariffs for the case that the constraint is binding and derive at what point the constraint restricts the optimal static network tariffs for dynamic consistency.

network tariff decreases due to the latter part of (5), i.e. $\hat{\tau}_n < \tau_n^*$. The opposite effect occurs in the south. From (6) it follows that $\hat{\tau}_s > \tau_s^*$. By setting $\hat{\tau}$ instead of τ^* the TSO deviates from the optimal static (unconstrained) volume-based network tariffs.

Consequently, this creates a deadweight loss in the current period to benefit the dynamically consistent allocation of future demand investments. While network tariffs rise in the south and, thus, lower consumer surplus there, network tariffs in the north decrease and increase consumer surplus. However, the increase in consumer surplus in the north does not compensate for the decrease in the south. The adjustments are not equal because of the ratio of the two demand functions, which would lead to higher (lower) network tariffs in the north (south) without the constraint for a dynamically consistent allocation of demand investments. For example, consider a situation where the demand function of the north is almost perfectly inelastic, and there is very price-sensitive demand in the south. Without the requirement for dynamic consistency, consumers in the north would bear most of the fixed network costs, while network tariffs in the south would be low. If the difference in network tariffs exceeds the difference in marginal generation costs, dynamic consistency is violated. In order to ensure dynamic consistency, the TSO reduces the network tariffs in the north. However, due to the inelastic demand in the north, consumer surplus increases only slightly. Conversely, increasing network tariffs in the south lead to a significant loss of consumer surplus.

3.4. Volume-based network tariffs under uniform pricing

In a regulatory setting with uniform pricing, the spot market clearing results in $p_i = c_n + \tau_i$. Total prices p_i may differ between the two nodes depending on the network tariffs τ_i.

The TSO maximizes welfare, anticipating the spot market result, her own budget and the dynamic consistency constraint (10a-10c). Due to uniform pricing, the spot market result is physically infeasible, and the TSO is obligated to redispatch generators. From this, the TSO bears additional costs that sum up to $C_{UP,\tau}^{TSO} = F + (c_s - c_n)(D_s(c_n + \tau_s^*) - \overline{L})$. In contrast to the other regulatory settings, the TSO's network costs depend on the network tariffs, because volume-based network tariffs impact the quantities demanded and they, in turn, impact redispatch costs.

$$\begin{aligned} \max_{\boldsymbol{\tau}} W_{UP,\boldsymbol{\tau}}(\boldsymbol{p}^*(\boldsymbol{\tau})) = &\int_{p_n^*=c_n+\tau_n}^{\infty} D_n(z)\,\mathrm{d}z + \int_{p_s^*=c_n+\tau_s}^{\infty} D_s(z)\,\mathrm{d}z \\ &+ \sum_i \tau_i D_i(p_i^*) - F - (c_s - c_n)(D_s(p_s^*) - \overline{L}) \end{aligned} \tag{10a}$$

$$s.t. \quad \sum_i \tau_i D_i(p_i^*) - F - (c_s - c_n)(D_s(p_s^*) - \overline{L}) = 0 \longrightarrow \lambda \tag{10b}$$

$$\tau_n^* \leq \tau_s^* \quad \longrightarrow \quad \mu \tag{10c}$$

The first-order conditions of the Lagrangian $\partial L / \partial \tau_i$ are no longer identical between north and south. The optimal network tariff in the north has the same structure as under zonal pricing, shown in (5). For the south, the optimal network tariff slightly changes to:

$$\tau_s^* = \frac{\lambda}{1+\lambda} \cdot \frac{D_s(c_s + \tau_s^*)}{-\frac{\partial D_s(c_s+\tau_s^*)}{\partial \tau_s^*}} + \frac{\mu}{1+\lambda} \cdot \frac{1}{-\frac{\partial D_s(c_s+\tau_s^*)}{\partial \tau_s^*}} - c_n + c_s \tag{11}$$

Compared to the structure derived under zonal pricing (6), the network tariff in the south consists of an additional component, which functions as a correction-term for redispatch. Under uniform pricing, the optimal volume-based network tariffs mimic zonal prices and partially correct for the inefficiency of the pricing scheme. Plugging equation (11) into the demand function of the south $D_s(c_n + \tau_s^*)$ yields a similar result as under zonal pricing, i.e. $D_s(c_s + \tau_s)$. However, the result is not equivalent to the setting under zonal pricing, as the values of the network tariffs τ_i differ.

Under uniform pricing, the ratio between the network tariffs not only depends on the ratio of the quasi-elasticities but also on the generation costs in the respective nodes. We derive the optimal network tariffs in Appendix C.3 and show the relationship in detail. Like in the setting under zonal pricing, the TSO might adjust the optimal static network tariffs if the dynamic consistency constraint is binding. The rationale is the same as under zonal pricing: Deviating from the optimal static (unconstrained) volume-based network tariffs creates a deadweight loss in the current period to the benefit of the dynamically consistent allocation of future demand investments. However, under uniform pricing, missing dynamic consistency is even more severe, as network tariffs are the only possibility of creating spatial price signals. Investments in the south would amplify the system costs by increasing redispatch and additionally increase the burden from network cost recovery for the consumers in the north.

4. Welfare implications of the different regulatory settings

In this chapter, we compare the four combinations of network tariffs and pricing schemes in terms of their static welfare. This way, we can show how different regulatory price components affect static efficiency and interact with each other. Based on the results of section 3, we further discuss the results for the static welfare in the context of a dynamically consistent allocation of demand investments. From sections 3.1- 3.4, we derive the optimal static welfare for each regulatory setting:
Fixed network tariffs and zonal pricing:

$$W^*_{ZP,f} = \int_{c_n}^{\infty} D_n(z)\,\mathrm{d}z + \int_{c_s}^{\infty} D_s(z)\,\mathrm{d}z - F + (c_s - c_n)\overline{L}, \tag{12}$$

Fixed network tariffs and uniform pricing:

$$W^*_{UP,f} = \int_{c_n}^{\infty} D_n(z)\,\mathrm{d}z + \int_{c_n}^{\infty} D_s(z)\,\mathrm{d}z - F - \big[(c_s - c_n)(D_s(c_n) - \overline{L})\big] \tag{13}$$

Volume-based network tariffs and zonal pricing:

$$W^*_{ZP,\tau} = \int_{c_n+\tau_n^{ZP*}}^{\infty} D_n(z)\,\mathrm{d}z + \int_{c_s+\tau_s^{ZP*}}^{\infty} D_s(z)\,\mathrm{d}z \tag{14}$$

Volume-based network tariffs and uniform pricing:

$$W^*_{UP,\tau} = \int_{c_n+\tau_n^{UP*}}^{\infty} D_n(z)\,\mathrm{d}z + \int_{c_n+\tau_s^{UP*}}^{\infty} D_s(z)\,\mathrm{d}z. \tag{15}$$

With volume-based network tariffs, the TSO's costs are indirectly displayed in the lower bounds of the integrals as per definition they are refinanced by the sum over all τ_i-payments. Note that the volume-based network tariffs are not identical under the two pricing schemes.
First, we analyze the isolated effects of changing either the pricing scheme or the network tariff design. Comparing zonal and uniform pricing with the same network tariff design, we show the

inherent inefficiency that results from the incomplete redispatch scheme under uniform pricing. With fixed network tariffs, the difference in welfare under zonal and uniform pricing is equal to:

$$\begin{aligned}\Delta W^{*}_{ZP,f-UP,f} &= (12) - (13) \\ &= (c_s - c_n) D_s(c_n) - \int_{c_n}^{c_s} D_s(z)\,\mathrm{d}z \\ &= \int_{c_n}^{c_s} D_s(c_n) - D_s(z)\,\mathrm{d}z > 0 \implies W_{ZP,\boldsymbol{f}} > W_{UP,\boldsymbol{f}}\end{aligned} \tag{16}$$

The result is always greater than zero as demand decreases in price. It is straightforward to show that the same relation holds with volume-based network tariffs, i.e. $W_{ZP,\boldsymbol{\tau}} > W_{UP,\boldsymbol{\tau}}$. Thus, regardless of the network tariff design, zonal pricing is welfare-superior to uniform pricing. Consumption at the spot market is higher under uniform pricing, as market-participants neglect transmission capacities. The TSO corrects the spot market result ex-post. Due to restricted participation of the supply-side, redispatch induces additional costs. The resulting welfare loss is depicted in the shaded triangle in the south in figure 2.

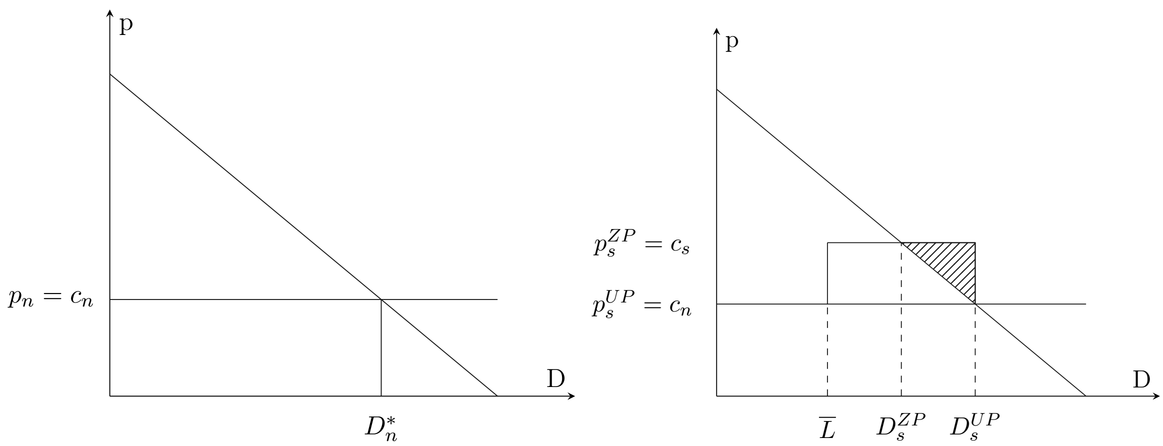

Figure 2: Additional costs from redispatch under uniform pricing compared to zonal pricing; both with fixed network tariffs.

Comparing welfare under zonal pricing with either fixed or volume-based network tariffs, we derive the inefficiency of volume-based network tariffs. Under zonal pricing, the difference in welfare with fixed and volume-based network tariffs yields:

$$
\begin{aligned}
\Delta W^{*}_{ZP,f-ZP,\tau} =& (12) - (14) \\
=& \int_{c_n}^{c_n+\tau_n^{ZP*}} D_n(z)\,\mathrm{d}z + \int_{c_s}^{c_s+\tau_s^{ZP*}} D_s(z)\,\mathrm{d}z - F + (c_s - c_n)\overline{L} \\
=& \int_{c_n}^{c_n+\tau_n^{ZP*}} D_n(z)\,\mathrm{d}z + \int_{c_s}^{c_s+\tau_s^{ZP*}} D_s(z)\,\mathrm{d}z - \sum_i \tau_i^{ZP*} D_i(c_i + \tau_i^{ZP*}) \qquad (17) \\
=& \int_{c_n}^{c_n+\tau_n^{ZP*}} D_n(z) - D_n(c_n + \tau_n^{ZP*})\,\mathrm{d}z + \int_{c_s}^{c_s+\tau_s^{ZP*}} D_s(z) - D_s(c_s + \tau_s^{ZP*})\,\mathrm{d}z \\
>& 0 \implies W_{ZP,f} > W_{ZP,\boldsymbol{\tau}}
\end{aligned}
$$

Since $z < c_i + \tau_i$ and demand decreases in price, the welfare difference must always be positive. According to economic theory, fixed network tariffs are welfare-neutral from a static perspective, whereas volume-based network tariffs cause a deadweight-loss. Figure 3 depicts the deadweight loss in the static setting, which is in both nodes depicted in shaded triangles.

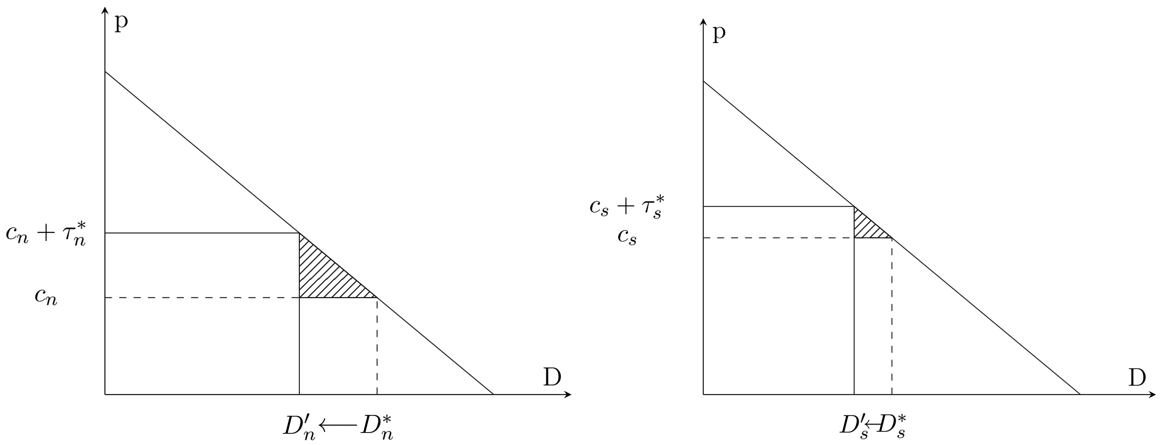

Figure 3: Deadweight loss associated with volume-based network tariffs under zonal pricing.

One could now assume that when applying uniform pricing, the relationship between the network tariffs is identical with the one under zonal pricing, or the inefficient pricing scheme even increases the inefficiency of the network tariff design. However, when both sources of inefficiency are present, it is not so clear-cut, as the following comparison between uniform pricing with fixed tariffs and volume-based network tariffs shows:

$$\begin{aligned}\Delta W^*_{UP,f-UP,\tau} =&(13) - (15)\\ =&\int_{c_n}^{c_n+\tau_n^{UP*}} D_n(z)\,\mathrm{d}z + \int_{c_n}^{c_n+\tau_s^{UP*}} D_s(z)\,\mathrm{d}z - F - (c_s - c_n)(D_s(c_n) - \overline{L})\\ =&\int_{c_n}^{c_n+\tau_n^{UP*}} D_n(z)\,\mathrm{d}z + \int_{c_n}^{c_n+\tau_s^{UP*}} D_s(z)\,\mathrm{d}z - \sum_i \tau_i^{UP*} D_i(c_n + \tau_i^{UP*})\\ &- (c_s - c_n)(D_s(c_n) - Ds(c_n + \tau_i^{UP*}))\\ =&\int_{c_n}^{c_n+\tau_n^{UP*}} D_n(z) - D_n(c_n + \tau_n^{UP*})\,\mathrm{d}z + \int_{c_n}^{c_n+\tau_s^{UP*}} D_s(z) - D_s(c_n + \tau_s^{UP*})\,\mathrm{d}z\\ &- (c_s - c_n)(D_s(c_n) - D_s(c_n + \tau_s^{UP*}))\end{aligned} \tag{18}$$

The result can be either positive or negative, meaning that the welfare effect is ambiguous. On the one hand, fixed network tariffs do not impact the spot market result, while volume-based network tariffs induce a deadweight loss. On the other hand, equation (18) shows that the redispatch costs differ between the two network tariff designs. Since the quantity demanded in the south is lower with volume-based network tariffs, the market outcome requires less redispatch than the setting with fixed network tariffs. However, this is not only due to the general demand reduction associated with the higher prices in both nodes. As shown in equation (11), the optimal volume-based network tariff in the south includes a correction term that accounts for the difference in marginal generation costs between both nodes and, therefore, structurally reduces demand in the south. If the welfare-enhancing effect of reducing redispatch costs exceeds the deadweight loss, volume-based network tariffs can increase overall welfare. Whether this is the case depends on the particular demand functions.

Proposition 3. *If multiple market inefficiencies are present through the pricing scheme and network tariff design, it may not be sufficient to offset only one distortion. Uniform pricing with volume-based network tariffs can outperform a regulatory setting of uniform pricing and fixed network tariffs if the redispatch costs outweigh the deadweight loss of volume-based tariffs. Vice versa, the higher the fixed costs of the network, the more likely it is that regulation with fixed network tariffs is welfare superior.*

We analyze the interactions if both the network tariff design and the pricing scheme are varied between the two settings. To do so, we compare the welfare under uniform pricing and fixed network tariffs with the welfare under zonal pricing and volume-based network tariffs:

$$
\begin{aligned}
\Delta W^*_{UP,f-ZP,\tau} &= (13) - (14) \\
&= \int_{c_n}^{c_n+\tau_n^{ZP*}} D_n(z)\,\mathrm{d}z + \int_{c_n}^{c_s+\tau_s^{ZP*}} D_s(z)\,\mathrm{d}z - F - (c_s - c_n)(D_s(c_n) - \overline{L}) \\
&= \int_{c_n}^{c_n+\tau_n^{ZP*}} D_n(z) - D_n(c_n + \tau_n^{ZP*})\,\mathrm{d}z + \int_{c_n}^{c_s+\tau_s^{ZP*}} D_s(z) - D_s(c_s + \tau_s^{ZP*})\,\mathrm{d}z \\
&\quad - (c_s - c_n) D_s(c_n)
\end{aligned} \tag{19}
$$

The result can also be either positive or negative. In this case, the overall effect on welfare depends on whether the deadweight loss from volume-based tariffs, i.e., the inefficiency of the welfare inferior network tariff design, or the redispatch costs under uniform pricing, i.e., the inefficiency of the welfare inferior pricing scheme, predominates.

If the redispatch costs are high enough, they can exceed the deadweight loss from volume-based network tariffs, making zonal pricing with volume-based network tariffs welfare superior. Hence, the higher the inefficiency of redispatch is, the more important the pricing scheme is to manage congestion. Vice versa, if fixed network costs rise, it becomes more likely that the fixed network tariffs become welfare superior as the inefficiency of volume-based network tariffs outweighs the redispatch costs in $W^*_{UP,f}$. Using (19), we can show that with rising F, the welfare difference between the two network tariff designs increases, i.e. $\partial \Delta W^*_{UP,f-ZP,\tau} / \partial F > 0$. From equation (9), we can derive that with increasing fixed network costs F, the network tariffs in both nodes increase, too, i.e., $\partial \tau_i^{ZP*} / \partial F > 0 \; \forall i$. It is straightforward to show that $\partial \Delta W^*_{UP,f-ZP,\tau} / \partial \tau_i^{ZP*} > 0$. Therefore, with volume-based network tariffs, the deadweight loss increases as fixed network costs rise. Thus, from a welfare perspective, the higher the fixed network costs F rise, the more advantageous the application of fixed network tariffs becomes.

For the sake of completeness, the difference between $W^*_{ZP,f}$ and $W^*_{UP,\tau}$ can be derived from the results above: $W^*_{UP,\tau} < W^*_{ZP,\tau} < W^*_{ZP,f}$ and thus, $\Delta W^*_{ZP,f-UP,\tau} > 0$. Figure 4 summarizes the findings.

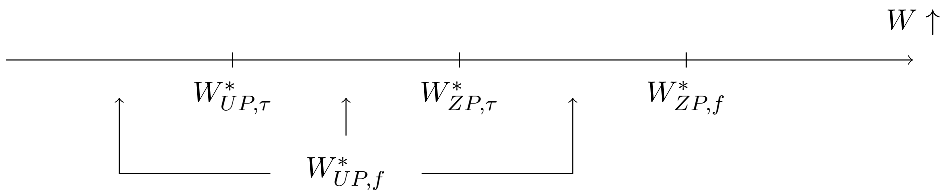

Figure 4: Welfare comparison of the different regulatory settings.

Ranking the regulatory settings in terms of static welfare demonstrates the importance of addressing the interactions between price components. Contrary to the first intuition, there is no clear order regarding the four analyzed settings. Our analysis finds that the distortions of one regulatory element can either amplify or compensate for the distortions of another element. If either the pricing scheme or the network tariff design leads to inefficiencies, it is best addressed by restructuring the respective price component. However, suppose both sources of inefficiency are present. In that case, i.e., the combination of uniform pricing and volume-based network tariffs, an adjustment of only one aspect can have unintended, welfare-adverse effects. As optimal volume-based network tariffs structurally reduce redispatch costs, it is impossible to ensure that switching to fixed network tariffs increases market efficiency. Due to this compensation effect, the two inefficiencies can perform better than a regulatory setting with only one inefficiency in place. This compensation effect is particularly relevant for the static welfare, the higher the costs for redispatch are.

As section 3 shows, the static welfare of the four regulatory settings interacts with the requirements for dynamic consistency. The interaction can be divided into two main effects. The first interaction occurs in regulatory settings with volume-based tariffs. The TSO reduces static welfare in the regulatory settings with volume-based network tariffs if it is necessary to adjust the optimal (static) network tariffs to ensure dynamic consistency. Under zonal pricing, this adjustment only increases the deadweight loss. Under uniform pricing, this adjustment additionally increases the compensation effect. The redispatch costs decrease as the volume-based network tariffs in the south increase to ensure dynamic consistency. This effect partially makes up for the increase in deadweight loss. However, the overall static welfare still decreases due to the adjustment of the volume-based network tariffs. In contrast, the TSO can adjust fixed network tariffs without impacting the static welfare to ensure dynamic consistency. Hence, the welfare-ranking of the regulatory settings changes if the

TSO must adjust the volume-based network tariffs to ensure dynamic consistency. It becomes more likely that the regulatory setting with fixed network tariffs and uniform pricing is welfare superior to the regulatory settings with volume-based network tariffs. Second, the importance of dynamically consistent network tariffs increases with the difference in generation costs, regardless of the network tariff design. Under zonal pricing, misaligned demand-side investments, i.e., investments in the south, would lead to higher generation costs in the future and, therefore, lower consumer surplus. Under uniform pricing, costs for redispatch would increase. To prevent congestion from being further exacerbated in the future, investment decisions should be made dynamically consistent. Thus, there is a bi-directional relationship between dynamic consistency of network tariffs and static welfare that policymakers should account for when changing the regulatory setting.

5. Conclusion

The transformation of the energy system from mainly inelastic consumers towards active market participants challenges the principles of network tariff design. If appropriately designed, network tariffs can serve as a coordination mechanism between the network operator and market participants. Otherwise, network tariffs can distort efficient price signals.

In an analytical model, we examine different regulatory settings, consisting of alternative spot market pricing schemes and network tariff designs, while considering a dynamically consistent allocation of demand investments. In our analysis, we assess the interactions of spot market pricing schemes and network tariff designs. The regulatory setting with zonal pricing and fixed network tariffs yields the highest welfare. A deviation of either the pricing scheme or the network tariff design leads to inefficiency. While under uniform pricing, additional costs occur due to redispatch, the application of volume-based network tariffs leads to a deadweight loss at the spot market. If both sources of inefficiency are present, i.e., the combination of uniform pricing and volume-based network tariffs, an adjustment of one single aspect can have unintended effects on overall welfare. As optimal volume-based network tariffs structurally reduce redispatch costs, it is not possible to ensure that market efficiency increases by switching to fixed network tariffs. Besides the network tariff design, network operators must pay additional attention to the allocation of network costs. It affects spatial price signals and, therefore, the dynamic allocation of demand investments. The restrictions on cost allocation are tighter under uniform pricing, as network tariffs are the only spatial price signal. However, under both pricing schemes, the TSO can ensure a dynamically consistent allocation of demand investments with fixed network tariffs without adversely affecting welfare. In contrast, with volume-based tariffs, the case may arise where the TSO must trade off between static welfare and dynamic consistency. The TSO can adjust the volume-based network tariffs deviating from the optimal static network tariffs to ensure dynamic consistency. By doing so, the TSO reduces static welfare in benefit of a dynamically consistent allocation of demand investments.

In current political debates, pricing schemes and network tariffs are often discussed separately. Our results highlight the relevance of jointly assessing network tariffs and pricing schemes for policy-makers and regulating authorities. Our results are important, considering that today's electricity systems often use a combination of uniform pricing and mainly volume-based network tariffs. In such a regulatory setting, it seems advisable to identify the predominating inefficiency instead of partly adjusting the regulatory setting. Especially when a change to zonal pricing and fixed network tariffs seems unlikely, regulators could consider the possibility of using volume-based tariffs in favor of their steering possibilities. Our analysis suggests that an integrated regulatory framework is important to avoid unintended distortions.

Moreover, regulators tend to use simplified rules for cost allocation in practice, which are not aligned with spot market prices and typically do not consider dynamic consistency. Spatial price signals become more important in a system under transition as they impact investment decisions. Therefore, these cost allocation rules have an essential impact on static welfare and dynamic consistency, especially in regulatory settings with uniform pricing.

Future research could include other network tariff designs such as general non-linear tariffs. Those tariffs could improve system efficiency and compensate for the frictions of distorted price components. The analytical model could further be expanded by including concerns on zonal pricing in practice, e.g., market power and illiquid markets. In addition, empirical studies could complement our theoretical findings to distinguish between the ambiguities that we found in our theoretical model and measure the associated welfare loss for the static and dynamic effects.

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Appendix A. Optimal spot market result

Consider a social planner solving the optimization problem (A.1a-A.1e). The social planner maximizes overall welfare, consisting of the consumer surplus from the participation at the spot market minus the electricity generation costs. Thus, she jointly optimizes the cost-minimal dispatch at the spot market level. The solution is constrained by the equilibrium condition, which requires supply to equal demand (A.1b-A.1c) and the restriction of the transmission line (A.1d).

$$\max_{l,\mathbf{q},\mathbf{D}} W = \int_0^{D_n} [p_n(z)]\,\mathrm{d}z + \int_0^{D_s} [p_s(z)]\,\mathrm{d}z - \sum_i c_i q_i \tag{A.1a}$$

$$s.t. \quad D_n + l = q_n \tag{A.1b}$$

$$D_s - l = q_s \tag{A.1c}$$

$$|l| \leq \overline{L} \tag{A.1d}$$

$$q_n, q_s, D_n, D_s \geq 0 \tag{A.1e}$$

The optimal solution yields a node-specific result. The optimal level of generation in each node is given by (A.2) and depends on the spatial choice of the demand investment.

$$q_i^* = \begin{cases} D_n^* + \overline{L} & \text{for } i = n \\ D_s^* - \overline{L} & \text{for } i = s \end{cases} \tag{A.2}$$

Since by assumption, generation costs are higher in the south and demand exceeds the capacity limit of the transmission line, the network is congested and fully utilized up to the capacity limit, i.e. $l^* = \overline{L}$. The prices reflect the marginal costs at the respective nodes with $p_n^* = c_n$ and $p_s^* = c_s$ and thus, producer surplus equals zero. Due to the price difference between the nodes and the quantity transmitted from node n to node s, a positive congestion rent $(c_s - c_n)\overline{L}$ results, which is accounted to the TSO budget.

Appendix B. Fixed network tariffs

The first-order conditions of the Lagrangian of the optimization problem (2a-2c) are:

$$\frac{\partial L}{\partial f_n} = \lambda\omega_n - \mu = 0 \tag{B.1}$$

$$\frac{\partial L}{\partial f_s} = \lambda\omega_s + \mu = 0 \tag{B.2}$$

$$\frac{\partial L}{\partial \lambda} = \sum_i \omega_i f_i - F + (c_s - c_n)\overline{L} = 0 \tag{B.3}$$

$$\mu\frac{\partial L}{\partial \mu} = \mu[c_s\overline{D} + f_s - c_n\overline{D} - f_n] = 0 \tag{B.4}$$

$$\frac{\partial L}{\partial \mu} = c_n\overline{D} + f_n \leq c_s\overline{D} + f_s \tag{B.5}$$

$$\mu \geq 0 \tag{B.6}$$

The complementary slackness condition (B.4) is true if either (1) $\mu = 0$, (2) $c_n\overline{D} + f_n = c_s\overline{D} + f_s$, or (3) both.

Case 1: $\mu = 0$. Plugging $\mu = 0$ into the first two equations yield $\lambda = 0$, as $\omega_i > 0$. The fixed network tariffs $\boldsymbol{f}$ can take every possible values that satisfy equation (B.3) and (B.5).

Case 2: $\mu > 0$ and $c_n\overline{D} + f_n = c_s\overline{D} + f_s$. Using the equality, we can solve for the fixed network tariffs, e.g. $f_s = \frac{F-(c_s-c_n)(\overline{L}+\overline{D}\omega_n)}{\omega_n+\omega_s}$. In addition, $\lambda = \frac{-\mu}{\omega_s}$ and $\lambda = \frac{\mu}{\omega_n}$. We can rule this case out, as it would require $\omega_n = -\omega_s$.

Case 3: $\mu = 0$ and $c_n\overline{D} + f_n = c_s\overline{D} + f_s$. Again, we can solve for the fixed network tariffs, e.g. $f_s = \frac{F-(c_s-c_n)(\overline{L}+\overline{D}\omega_n)}{\omega_n+\omega_s}$. Again, plugging $\mu = 0$ into the first equation yields $\lambda = 0$.

Hence, cases 1 and 3 are possible solutions of the optimization and both require $\lambda = 0$. As the shadow variable of the budget constraint is zero, the constraint (and the fixed network tariffs) has no influence on social welfare. Hence, fixed network tariffs can be considered as a welfare neutral payment.

Appendix C. Volume-based network tariffs

Appendix C.1. Deriving the Ramsey-Boiteux inverse elasticity rule

We use equation (7), substitute $p_i = c_i + \tau_i$ on the right-hand side and make use of the relationship $\tau_i = p_i - c_i$ to expand the equation. We denote the elasticity of demand with

$$\epsilon_i(p_i) = -\frac{\partial D_i(p_i)/\partial p_i}{D_i(p_i)/p_i} \tag{C.1}$$

Plugging the elasticity in, we then obtain the Ramsey-Boiteux formula, which is the classical inverse elasticity rule:

$$\frac{p_i - c_i}{p_i} = \frac{\lambda}{\lambda + 1} \cdot \frac{1}{\epsilon_i(p_i)} \tag{C.2}$$

We can see that a change in price ∂p_i is equivalent to a change in network tariff $\partial \tau_i$.

Appendix C.2. Solution for restricted volume-based network tariffs and boundary for binding dynamic consistency constraint

To solve for the optimal volume-based network tariff with a binding dynamic consistency constraint, we use the relation of network tariffs from (4b) and (4c). As (4c) is binding, it follows that $\tau_n = \tau_s + c_s - c_n$. Using the budget constraint (4b), we yield

$$\hat{\tau}_s = \frac{F - (c_s - c_n)(\overline{L} + D_n(c_n + \hat{\tau}_n))}{D_s(c_s + \hat{\tau}_s) + D_n(c_n + \hat{\tau}_n)} \tag{C.3}$$

and

$$\hat{\tau}_n = c_s - c_n + \frac{F - (c_s - c_n)(\overline{L} + D_n(c_n + \hat{\tau}_n))}{D_s(c_s + \hat{\tau}_s) + D_n(c_n + \hat{\tau}_n)}. \tag{C.4}$$

To derive the boundary at which the dynamic efficiency constraint is binding, we plug in the optimal static volume-based network tariff (9) into $c_n + \tau_n^* = c_s + \tau_s^*$:

$$c_n + \frac{F - (c_s - c_n)\overline{L}}{\frac{\rho_n(\tau_n^*)}{\rho_s(\tau_s^*)} D_s(c_s + \tau_s^*) + D_n(c_n + \tau_n^*)} = c_s + \frac{F - (c_s - c_n)\overline{L}}{\frac{\rho_s(\tau_s^*)}{\rho_n(\tau_n^*)} D_n(c_n + \tau_n^*) + D_s(c_s + \tau_s^*)}, \tag{C.5}$$

which simplifies to

$$\frac{\frac{\partial D_s(c_s + \tau_s^*)}{\partial \tau_s^*} D_n(c_n + \tau_n^*) - \frac{\partial D_n(c_n + \tau_n^*)}{\partial \tau_n^*} D_s(c_s + \tau_s^*)}{\frac{\partial D_n(c_n + \tau_n^*)}{\partial \tau_n^*} D_s(c_s + \tau_s^*)^2 + \frac{\partial D_s(c_s + \tau_s^*)}{\partial \tau_s^*} D_n(c_n + \tau_n^*)^2} = \frac{c_s - c_n}{F - (c_s - c_n)\overline{L}}. \tag{C.6}$$

The solution depends on the costs that need to be recovered, the relation of the generation costs and the relation of the demand functions in the respective nodes.

Appendix C.3. Volume-based network tariffs under uniform pricing

To solve for the case that the dynamic efficiency constraint is non-binding, i.e., $\mu = 0$, we make use of equation (11) and substitute the quasi-elasticity ρ_i.

$$\tau_s^* = \frac{\rho_n(\tau_n^*)}{\rho_s(\tau_s^*)}\tau_n^* + c_s - c_n \tag{C.7}$$

It still holds that the elasticity in one node affects the network tariff in the other node. In addition, the network tariffs also depend on marginal generation costs. Again, we can solve for the respective network tariffs using the budget constraint of the TSO. The network tariff in the south is equal to:

$$\tau_s^* = \frac{F - (c_s - c_n)\overline{L}}{\frac{\rho_s(\tau_s^*)}{\rho_n(\tau_n^*)} D_n(c_n + \tau_n^*) + D_s(c_n + \tau_s^*)} + c_s - c_n, \tag{C.8}$$

while the structure of the solution for the north is similar to the one under zonal pricing:

$$\tau_n^* = \frac{F - (c_s - c_n)\overline{L}}{\frac{\rho_n(\tau_n^*)}{\rho_s(\tau_s^*)} D_s(c_n + \tau_s^*) + D_n(c_n + \tau_n^*)} \tag{C.9}$$

For the case that the dynamic efficiency constraint is binding, we can use (10b) and (10c). This yields:

$$\hat{\tau}_s = \hat{\tau}_n = \frac{F - (c_s - c_n)(\overline{L} + D_s(c_s + \hat{\tau}_s))}{D_s(c_s + \hat{\tau}_s) + D_n(c_n + \hat{\tau}_s)} \tag{C.10}$$

We can check when the dynamic efficiency constraint gets binding, by substituting (C.8) and (C.9) into $\tau_n \leq \tau_s$:

$$\begin{aligned} &D_n(c_n + \tau_n^*)\tfrac{\partial D_s(c_s+\tau_s^*)}{\partial \tau_s^*}[R + (c_n - c_s)D_s(c_s + \tau_s^*)] \leq \tfrac{\partial D_n(c_n+\tau_n^*)}{\partial \tau_n^*} D_s(c_s + \tau_s^*)[R + (c_n - c_s)D_n(c_n + \tau_n^*)] \\ &\text{with} \quad R = F - (c_s - c_n)\overline{L} \end{aligned} \tag{C.11}$$

The result is similar to the regulatory setting with zonal pricing and depends on the costs that need to be recovered, the relation of the generation costs and the relation of the demand functions in the respective nodes.