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Understanding Society

Providing efficient network access to green power generators: A long-term property rights perspective.*

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Abstract

Coordinating the timing of new production facilities is one of the challenges of liberalized power sectors. It is complicated by the presence of transmission bottlenecks, oligopolistic competition and the unknown prospects of low-carbon technologies. We build a model encompassing a late and early investment stage, an existing dirty (brown) and a future clean (green) technology and a single transmission bottleneck, and compare dynamic efficiency of several market designs. Allocating network access on a short-term competitive basis distorts investment decisions, as brown firms will preempt green competitors by investing early. Dynamic efficiency is restored with long-term transmission rights that can be traded on a secondary market. We show that dynamic efficiency does not require the existence of physical rights for accessing the transmission line, but financial rights on receiving the scarcity revenues generated by the transmission line suffice.

Keywords: network access, congestion management, renewable energy sources, power markets

JEL-codes: L94, L13, C72, D43.

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1 Introduction

Before the liberalization of the energy sector, generation investments were centrally planned and coordinated. This implied that interactions between different power plants through network constraints were fully taken into account during investment appraisals. Indeed, because of transmission constraints, operating a new power plant may require existing plants to cut-back production and preclude otherwise profitable future investments. In a liberalized market, investment coordination takes place through the market and transmission market design needs to induce firms to internalize those interaction effects.

We build a bare-bones model to compare different transmission market designs taking into account the dynamic nature of generation investments. The set-up of the model is inspired by current power markets, which are characterized by oligopolistic competition and a drive for low-carbon but capital intensive technologies whose future costs are still uncertain. In order to model the dynamic interaction of investments we develop a two-stage entry game with two firms: a first-mover (the 'brown' incumbent) and a second mover (the 'green' entrant). The brown incumbent uses a mature conventional production technology such as coal or natural gas with known low investment costs and a high marginal cost. The green entrant uses a low-carbon technology such as wind or solar power which will only become available in the second stage. Its investment costs are initially unknown. We assume that all externalities are internalized by firms. That is, the marginal costs include not only the fuel, operation and maintenance cost, but also the social cost of CO_2 emissions and other pollutants. Hence the green and brown technologies differ only in their maturity and the relative importance of marginal and investment costs. The timing is as follows: In period 1, the incumbent decides whether to invest immediately or to delay its decision until period 2. The entrant only decides on investing in period 2. The transmission bottleneck is modeled as a single line which firms need to use to reach consumers. Its capacity is such that it can only transport the production output of single firm. The bottleneck is owned by a regulated network owner, who always makes available all transmission capacity to the market.

This set-up provides for some interesting features. (1) In the first period, the incumbent faces a real option problem on whether to it invest or delay the investment decision. Strategic considerations might lead the incumbent to invest early in order to deter entry. How do we ensure that incumbent's decisions are socially efficient? (2) Once the entrant has installed its production plant, it can out-compete the incumbent to access the bottleneck, as its energy is available for free. The incumbent's power plant then becomes obsolete. Should the incumbent be compensated for its stranded assets, as it has lost its implied right on network capacity?

We consider three market designs. The first design, the nodal spot market, consists of a short-term market in which an auctioneer jointly clears energy and transmission markets after collecting producers' supply offers and consumers' demand bids. In this design there are no long-term property rights for transmission. In the second design a long-term financial transmission right market is added to the nodal spot market. The owner of a financial transmission rights (FTR) receives the revenues that are generated by selling access to the bottleneck in the nodal sport market. Hence, the owner receives the proceeds generated by the transmission line (ius fructendi), but cannot affect who will use the transmission line as this is determined by the auctioneer. The third design has long-term physical transmission rights for the bottleneck. The owner of the physical rights can decide whether to use or not use the bottleneck capacity (ius utendi). In the latter two designs transmission rights are long-term, that is they cover two investment periods. They are allocated before the first stage in a primary market. If resale is allowed (ius vendendi) the transmission rights can be resold in a secondary transmission market.

With nodal spot pricing, the incumbent will invest too often for the following two reasons. The incumbent does not fully internalize the social real option value of waiting, as it does not internalize the profit of the entrant and the congestion revenue collected by the network owner. Moreover, it will strategically enter early to deter entry and reduce competition. Compensating the incumbent by for instance grandfathering long-term non-tradable financial transmission rights to the incumbent, only exacerbates this problem. The intuition is the following: Financial transmission right will only be valuable if there is competition for using the bottleneck. Hence, the incumbent will invest early, as this increases competition. Dynamic efficiency can be restored by allowing the resale of transmission rights. As early investment lowers the resale value of the transmission rights, the incumbent will delay investments to the socially optimal level. By reselling a physical transmission right, the incumbent can extract the entrant's profits and therefore internalizes the entrant's profit. We show that dynamic efficiency does not require those long-term transmission rights to be physical. Also with financial transmission rights we obtain dynamic efficiency. If the incumbent would not have full bargaining power in the secondary market, it will not fully extract the profits of the entrant and the outcome is not dynamically efficient. However, dynamic efficiency can be restored, if transmission rights are auctioned in the primary market.

Related literature

The set-up of our model is somewhat similar to Aghion and Bolton (1987), in which an incumbent and a consumer sign an exclusive long term contract with a penalty for breach, in order to extract rents from a entrant with unknown production costs. By signing the exclusivity contract, the entrant, if it enters, is obliged to sell at a low price in order to compensate the consumer for penalty of breaching the contract with the incumbent. Hence, jointly the incumbent and the consumer can extract some of the efficiency gains from the entrant. However, as a result some efficient entry is deterred. Also in our model the incumbent faces an entrant with unknown production costs, and can foreclose entry by obtaining a physical transmission contract. However, the incumbent does not negotiate a contract with *consumers*, but it buys the contract from an independent network operator and the entrant does not bargain with consumers about the price of its goods, but with the incumbent for obtaining the transmission access.[1] Moreover, bargaining between the

[1]Note that in our model consumers are indifferent regarding the investment decisions of incumbent and entrant, as they are assumed to be located in a large competitive high cost market downstream of the bottleneck. Their energy price depends on those local production costs, but not on upstream competition. They are therefore modeled as passive participants.

incumbent and the entrant is assumed to be efficient, and therefore, in contrast to Aghion and Bolton (1987) entry is always ex-post efficient. The sharing of the bargaining surplus affects the incentives for the incumbent to invest in the first stage (which is not covered by Aghion and Bolton). The larger the incumbent's share of the bargaining surplus, the more it will internalize the entrant's profits, and the less incentives the incumbent has to deter entry by investing early. Summarizing, it is more efficient to use the transmission contract to extract rents from the entrant, than to over-invest in the first stage. Such transmission rights might therefore improve long term efficiency. Interestingly, even if the incumbent has no full bargaining power in the secondary market, (and cannot fully extract the entrant's rents), efficiency is restored if rights are allocated initially in a competitive primary market.

Given irreversibly of investments the incumbent faces a real option problem in the first stage (Dixit and Pindyk, 1994). We show that strategic considerations reduce the real option value of delaying investments and creates a first mover benefit for the incumbent, which both lead to investments which are earlier than socially optimal. This is similar to Grenadier (2002) who shows that competition reduces real option values in a Cournot framework, which leads to earlier investments.[2] However, our setting differs as we study different transmission market designs.

Our paper is linked to the literature on property rights, nuisance and compensation, which studies for instance whether an airport should compensate residents living around the airport for noise pollution, even if those residents arrive after the airport's establishment.[3] Pitchford and Snyder (2003) show that allocating the property rights to the first mover (the airport) eliminates underinvestments by the first mover due to a hold-up problem (and hence justify the legal "coming to the nuisance" doctrine). However, it might lead to overinvestment by the first mover, as early investments improves its bargaining position vis-a-vis the residents. In some cases it might therefore be optimal to allocate rights the second mover (the residents). We extend the model by Pitchford and Snyder by allowing for trade of property rights both in the primary and the secondary market, by considering additional property rights regimes such as financial transmission rights, and by considering firms that compete in the same product market (and hence externalities are market based).

Our paper is indirectly linked to the literature of property rights, takings and compensation, which studies whether a firm that invests on land which is subsequently taken by government for other use, should receive a compensation for its sunk investments. In practice, many incumbent generators built power plants in a pre-liberalization era, where network access was guaranteed by the regulator and subsidies for renewable energy were small or non-existent. When governments liberalized markets, introduced regulated network access, and massively subsidized green energy, the incumbent would often (implicitly) loose its access right. The standard result of the literature in such a situation is the zero compensation result (Blume et al. 1984 and Fischel and Shapiro, 1989): the government

[2]Similarly, Leahy (1993) shows that price-taking perfectly competitive firms will time their investments according to the social optimum, and can rely on an NPV rule.

[3]See also Wittman (1980, 1981).

should not compensate the incumbent firm. The intuition behind this surprising result is that when the investor decides to invest, she is aware of the possibility that its property (the land or the access right) will be taken by the government and hence, she fully internalizes the potential loss of the capital when she makes her investment decision. If instead compensation would have been given for the taking, the investor underestimates the potential loss of taking and overinvests. In many power markets, governments recognize those "historical access rights" by grandfathering transmission rights to the firm once it invests. We show that this type of compensation will result in overinvestment as predicted by the earlier literature. However, we also derive that if the compensation is made tradable in a secondary market, the Fischel and Shapiro result no longer holds, as the effect on the resale value reduces the incentives for early investments by the incumbent, which might restore efficiency. Hence, consideration regarding compensation and efficiency do no longer conflict.

Policy relevance. Many mature power markets use a single centralized auction to jointly clear short-term energy and transmission markets. In its purest form, the auction results in a different energy price for each network node and time period (nodal pricing).[4] Most U.S. power markets use this design. For political reasons, many European markets use a variation of this auction design in which prices can vary across geographical areas, but not within areas. Hence prices are not nodal but zonal. Our simplified model is representative for bottlenecks between nodes as well as between zones.

As markets evolve, often a system of financial transmission rights is introduced.[5] Those rights are used by market participants to manage the risk of their contracting and generation portfolio.[6] Financial transmission rights are typically sold on a centralized primary market and can then be re-traded in a secondary market. Sometimes they are also grandfathered to historical network users.[7] In our paper we study both grandfathering as well

[4] The auctioneer selects the lowest cost bids that balance energy supply and demand in each node given the transmission constraints and the physical laws governing the network flows. The market clearing price in a node is equal to the marginal cost of supplying energy to that node. Differences between nodal prices give rise to a trading surplus, which is collected by the network operator in the form of congestion rents on the transmission lines. One of the first advocates for nodal pricing in energy markets were Schweppe et al. (1988). Wilson (2002) argues that such a central design is necessary for short-term operational efficiency given the large number of inter-dependencies.

[5] Those rights are known under different names: Financial Transmission Rights (FTRs) in PJM, New England and Midwest markets; Transmission Congestion Contracts (TCCs) in the New York market; Congestion Revenue Rights (CRRs) in California and Texas; Transmission Congestion Rights (TCRs) in the Southwest Power Pool.

[6] For instance, a generator with production location A might sell a *financial* forward contract to consumers in location B. While this contract will fully hedge consumers against spot price fluctuations in their location, the generator will still face some basis risk. That is, spot prices in location A and B might not be perfectly correlated. A financial transmission rights allows the generator to hedge this basis risk.

Financial Transmission Rights could also be used to improve regulation of transmission investments as they provide information about (future) transmission service demand (Henze et al., 2012 and Rosellón and Weigt, 2011). For an early and more in depth discussion of FTRs see Hogan (1992). Rosellón and Kristiansen (2013) review the experiences and the theoretical foundations of Financial Transmission Rights.

[7] For instance in the Midwest ISO, firms receive "Auction Revenue Rights" based on their historical

as a primary market for financial transmission rights.

Some early power markets, often without well-developed spot markets, rely on a system of physical transmission rights. The owners of those rights can transport electricity across transmission bottlenecks. Gradually those physical transmission rights are being phased out, and they often receive properties that make them more alike financial rights. For instance, physical transmission rights now often come with use-it-or-loose-it rules, which frees transmission capacity that remains unscheduled for usage in the short term spot market.[8] We model the physical transmission right in its purest form, in which they can be used to exclude firms from using transmission capacity.

For bottlenecks within a zone, European markets use a special market design called counter trading. Under counter trading the energy market first clears as if there are no transmission bottlenecks within the area. Then, after market clearing, the network operator will manage congestion by paying some generators to reduce their production and others to increase production. We do not explicitly model counter trading, because in our setting it is equivalent to grandfathering non-tradable financial transmission rights to the incumbent. This leads to overinvestment by the incumbent. See also Dijk and Willems (2011) and Lazarcyk and Holmberg (2015).

To the best of our knowledge no other study on transmission market design studies the long-run efficiency of transmission contracts while explicitly modeling market power, dynamic investments and uncertainty. In a monopoly model without investments, Joskow and Tirole (2000) show that financial transmission rights are operationally, in the short-run, more efficient than physical transmission rights, as it allows for risk hedging, without allowing the monopolist to strategically foreclose its home market by withholding transmission capacity. Introducing a "use-it-or-loose-it" rule with the physical transmission rights eliminates this competitive concern. They also stress the importance of the specific design of the primary auction for transmission rights.[9] In contrast to Joskow and Tirole, we assume that the incumbent and the entrant are investing in the same location and compete for using the transmission line. Hence, although the incumbent can still foreclose the entrant by buying transmission rights, the incumbent is not trying to protect its home market.

Oxera (2003) estimates that around 80% of the benefits of locational signals result from the long-term effect of plant siting. Hence, only 20% comes from the short-term operational optimization of existing plants. This shows that the long-term effects that are the focus of this paper are very relevant. Lapuerta and Harris (2004) stress that those locational signals

network usage. Those ARRs are similar to long-term FTRs and can each year be converted into short-term FTRs (if certain feasibility constraints are satisfied), or provide its owners a fraction of the auction revenue of short-term FTRs.

[8]In meshed networks FTRs and PTRs also differ in their presentation of the network structure. FTRs are defined independent of the network topology as point-to-point transmission rights. PTRs are link-based and reflect the actual transmission lines more directly. FTRs often take the form of forward contracts, while PTRs are option contracts. As we do not focus on meshed networks, we refer to Hogan (1992) for a more in depth discussion.

[9]Gilbert, Neuhoff and Newbery (2004) extend this model to an oligopoly setting.

should reflect no more and no less than the cost to the transmission network of a siting decision. In our model we show that without transmission rights such a locational signal should take into account the real option value of alternative usages of the transmission line, and does not need to be related to the cost of investing in transmission capacity. Rious et al. (2009) show that the lumpiness in transmission investments greatly decreases differences in nodal prices with inefficient plant siting as a result. They therefore argue for an additional connection charge. Also in our model we obtain inefficient investments with nodal pricing, but the introduction of tradable long term transmission rights restores efficiency.

The remainder of this paper is organized as follows. Section 2 presents the framework of our model while section 3 investigates the efficiency of nodal spot pricing, with and without tradable financial and physical transmission rights. Section 4 discusses alternative sharing rules of the main model. Section 5 concludes.

2 Model

Consider an electricity market with one low cost, export-constrained generation area in the North and one large, high cost import-constrained area in the South that are connected by a transmission line with capacity K. Consumers are located exclusively in the South and are supplied by competitive retail companies which buy energy on the local wholesale market. Production in the South is competitive, and occurs at (high) marginal cost C_S. Demand in the South is high and exceeds the capacity of the transmission line. Hence, energy imports from the North are insufficient to meet demand, and additional production by southern generators is always necessary.[10] We develop a two-period stochastic investment model in which two firms, the incumbent (I) and the entrant (E), consider investing in the northern location. Production in the North is cost efficient, but transmission capacity limits business opportunities. The two firms have access to technologies which differ in maturity and cost structure. The entrant uses an innovative technology (for instance off-shore wind), which becomes available only in period 2, has low marginal cost, and, initially, uncertain investment costs. The incumbent uses a mature technology (such as a natural gas power plant) which is available already in period 1. Investments are assumed to be lumpy. Firms invests either a capacity equal to the size of the transmission line, K, or nothing at all.[11]

The incumbent and the entrant have marginal costs c and d, and (per unit) investment

[10] More precisely, with K units consumed in the South, the marginal willingness-to-pay of consumers exceeds the production and retail costs, i.e. $P_{cons}(K) > C_S + C_{retail}$, with $P_{cons}(\cdot)$ the inverse demand function of consumers.

[11] Investment lumpiness is a simplifying assumption. It is realistic for sufficiently small transmission lines, because there are economies of scale in building generation capacity both on plant and site level. Obviously, it is never optimal to build more than the capacity of the transmission line. As an extension of the main model, we investigate how allowing generators to have capacity lower than the transmission of the transmission line affect the main results of our study. As we will see to great extent, the results remain qualitatively the same.

costs F and G, respectively. The entrant has lower marginal cost than the incumbent ($c - d = \Delta c > 0$), and its fixed cost G is initially treated as a continuous stochastic variable on support $[0, \overline{G}]$ with cumulative density $\Phi(G)$. The distribution function of G is common knowledge. Total production cost in the North is always lower than the marginal production cost in the South, and for high realizations of G, the innovative technology is more expensive than the mature technology ($c + F < d + \overline{G} < C_S$).

Competition and investment in the North depend on transmission access regulation and the accompanying property rights regime. In what follows, we examine three three transmission mechanisms: (1) *Nodal pricing*, (2) *Nodal pricing with financial transmission rights*, and (3) *Physical transmission rights*. The mechanisms differ in whether we consider long-term transmission rights and whether these long-term rights are physical or financial. We also study how the existence of a secondary market for the trade of long-term rights and the way that the rights are initially allocated affect investment incentives.

Under nodal pricing, the transmission line is managed by the transmission system operator (TSO) who dispatches generators based upon their bids to supply generation services so as to balance the supply and demand for generation services in an efficient manner taking into account physical constraints on the transmission network. Nodal energy prices are determined by local demand and supply conditions and import (or export) levels. Differences in locational prices can vary widely over time. When there is no congestion on a transmission network, there is only one price on the interconnected system.[12] By contrast, if transmission lines are congested, the marginal energy prices will vary per location (node) and over time. The difference between locational prices represent the congestion charges, which are collected by the transmission system operator as scarcity rents.

In the setup of our paper nodal pricing implies the following: The incumbent and the entrant compete *á* la Bertrand for supplying energy services in the North. The TSO dispatches the generator with the lowest bid in the North, (unless this bid exceeds the marginal cost C_S in which case no generator is dispatched in the North). This generator receives a (per unit) payment equal to its bid b. The TSO pays the generator the price b for energy production, transports energy from North to South, receives the price C_S from retailers, and collects the congestion charge $K(C_S - b)$, the merchandising surplus.

Locational price variation in a nodal pricing model creates a demand by risk-averse agents for instruments to hedge against price fluctuations. One of the instruments to hedge against price fluctuations is called financial transmission rights (FTRs). FTRs insure the incumbent (or the entrant) against regional price differences and the associated congestion charges. In particular, these rights give the holders a financial claim on the congestion rents created when the network is constrained. In this paper, FTRs are auctioned or grandfathered to either the incumbent or the entrant at the start of the game. The effect of FTRs is that in case the holder faces competition, it is compensated for lower energy prices in the North as it receives the congestion rents. In case the holder is less efficient than the rival firm, in equilibrium, it is compensated for not producing. The holder of the

[12] We ignore Joule transmission losses in the system (i.e. electrical energy dissipating in the transmission lines as heat). If those losses are taken into account, location prices will reflect those transmission losses.

rights has the option to resell them to its rival firm.

An alternative regulatory model for network access is a system of physical transmission rights (PTRs). Under this approach, network access and congestion pricing are decentralized and only the holders of physical transmission rights are allowed to use congested transmission lines. Specifically, the physical capacity of all potentially congested interfaces is determined by the TSO, and property rights to use this capacity are defined and allocated to network users. A firm must possess a physical right to transport over the congested interface. The markets for these physical rights then determine the market-clearing prices for congestion. In this paper, PTRs are long-term, and therefore, give their holder the right to withhold access to its transmission property even when it decides not to enter the market. The property rights of the transmission line are auctioned either to the incumbent or the entrant at the start of the game. The holder of the rights has the option to resell them to its rival firm instead of using the line itself when it is profitable.

The timing of the game differs slightly between the three scenarios

- Before period 1, long-term transmission rights are allocated to a potential generator of the North. These transmission rights can be either PTRs or FTRs. In the absence of such rights the game starts in period 1 directly.
- Period 1: The incumbent chooses whether to enter the market by paying a fixed cost F or to wait. In case it enters it makes a per unit first period profit μ.[13] Between period 1 and 2, nature draws the fixed cost G of the entrant. The realization of G is common knowledge. In the PTR and FTR scenarios, following the realization of G, the owner of the long-term rights may make a take-it-or-leave sales offer to its competitor. The competitor accepts or rejects this offer.
- Period 2: The entrant and the incumbent (in the case that it did not enter the market in the first period) simultaneously decide whether they will enter the market. Note that when the incumbent enters in period 1, it remains in the market for the second period of the game without having the option to exit, so, in this case, in the second period, there is only one entry decision (to be made by the entrant).[14] In the nodal pricing and FTR scenario, firms choose their pricing behavior in the resulting Bertrand game. The TSO dispatches the firm with the lowest price bid. In the PTR scenario, a firm that owns PTRs and invested in production capacity supplies energy to the South directly.

[13] In the nodal pricing and FTR scenario, the incumbent submits an energy bid to the TSO for producing electricity. In equilibrium the TSO dispatches the incumbent and the transmission lines is used. In the PTR scenario, the incumbent will only enter if it owns PTRs. In that case the incumbent produces and transports energy to the South.

[14] For certain cost parameters, the simultaneous entry game might have multiple Nash equilibria. In pure strategies there are two Nash equilibria. One in which only the entrant enters and another one where only the incumbent enters. We assume that the firms co-ordinate on the pure Nash equilibrium that implies the lowest total cost. Hence, coordination failures in the second stage are not the source of inefficiencies in the model.

Both firms discount profits with discount factor $\delta < 1$. In addition, we assume that the incumbent cannot profitably enter the market unless it is active during the second period. Hence, its first period profit, μ is smaller than its investment cost F ($\mu < F$).[15] However, the incumbent's first period profit outweighs the extra capital costs of investing in period 1 (F) instead of delaying the investment until period 2 (δF). Hence,

$$F > \mu > (1-\delta)F, \tag{1}$$

which implies that $F - \mu < \delta F$. In the absence of strategic interactions, the incumbent always invests in period 1.

Before analyzing the investment strategies of the incumbent and the entrant in the three scenarios we first develop the social planner's investment policy as a benchmark case. Investment in the first period is socially optimal if the social benefit from investing is larger than the benefit from waiting. The social planner's payoff equals the sum of the incumbent's and the entrant's profits, the benefit received by the TSO, i.e. its merchandising surplus and consumers' surplus in the South. As there is a large competitive market in the South with marginal cost C_S, the equilibrium price in the South is independent of the investment decisions in the North, and consumer surplus is a constant. Hence, the optimal social outcome corresponds to the minimum total expected production cost. By investing in North, expensive production in the South can be avoided, but additional investment costs might be incurred. Hereafter, without loss of generality, we normalize the transmission capacity at $K = 1$.

Proposition 1. *Investment in period 1 is socially optimal if and only if the social value of early investment is positive:*

$$\Delta V_{SP} = \underbrace{\mu - (1-\delta)F}_{I} - \delta \left[\underbrace{\int_0^{\Delta c} F \, d\Phi(G)}_{IIa} + \underbrace{\int_{\Delta c}^{\Delta c + F} (F + \Delta c - G) \, d\Phi(G)}_{IIb} \right] > 0. \tag{2}$$

Proof. The expected cost reduction of investing early in the mature technology early is equal to:

$$V_{SP}^{Invest} = (\mu - F) + \delta \left[\int_0^{\Delta c} (C_S - d - G) d\Phi(G) + \int_{\Delta c}^{\overline{G}} (C_S - c) \, d\Phi(G) \right].$$

The first term represents social value of the first period cost reduction μ and the investment cost F. In the second period, the innovative technology will be used if $G < \Delta c$, in which case the cost reduction is equal to $c - d - G$. For higher cost realizations the mature technology remains in use, and the cost advantage is $C_s - c$.

[15] Let for example, periods 1 and 2 have a duration D_1 and D_2, respectively. The duration of the second period is normalized to $D_2 = 1$, while the first period is shorter ($D_1 < 1$). Then, the first period profit is $\mu \equiv D_1(C_S - c)K$. So, this consideration implies that the duration of the first period is sufficiently small.

The expected cost reduction with delayed investment decisions is equal to:

$$V_{SP}^{Wait} = \delta \left[\int_0^{\Delta c+F} (C_S - d - G) d\Phi(G) + \int_{\Delta c+F}^{\overline{G}} (C_S - c - F)\, d\Phi(G) \right].$$

There is no cost reduction in the first period. In the second period the innovative technology will be used whenever $G < \Delta c + F$, in which case the cost advantage is $C_S - d - G$, otherwise the mature technology is optimal, with cost advantage $C_s - c - F$. Investing early is socially optimal whenever $\Delta V_{SP} = V_{SP}^{Invest} - V_{SP}^{Wait} > 0$, which simplifies to equation (2). □

In expression (2), part I is the net present value of an early investment. By investing earlier, the firm generates profit μ but the investment cost is incurred earlier, so there is a loss: $(1-\delta)F$. Given assumption (1) this term is positive. Parts IIa and IIb represent the social real option value of waiting. By investing in period 1, one forgoes the benefit of learning more about the future cost G. Ex-post, if one learns that the cost of the entrant G is low, it would have been cheaper to let the entrant produce. If the entrant is very efficient, $G < \Delta c$, one will no longer use the incumbent's technology, and the investment cost F is sunk. While if the investments costs of the entrant are intermediate, $\Delta c < G < F + \Delta c$, the incumbent's investment will be used, but the entrant would have had a lower total production cost. Hence learning could have lowered total production costs with $(c + F) - (d + G)$.

It is straightforward from (2) that early investment becomes more attractive for a higher discount rate δ, higher first period profit μ, and lower investments cost F. Note that if there are no irreversible costs are incurred ($F = 0$), then the real option value (term IIa+IIb) becomes zero.

3 Analysis

This section investigates how access regulation affects the incumbent's and the entrant's investment strategies for the scenarios described above.

3.1 Nodal Pricing

Given our assumptions, and conditional on the first period investment, we will show that the second period investments are efficient. So, dynamic efficiency depends on whether private incentives for investment in period 1 coincide with the social investment incentives. Proposition 2 summarizes those investment decisions.

Proposition 2. *Under nodal pricing, the incumbent invests in period 1 if and only if*

$$\Delta\Pi_{NP} = \underbrace{\mu - (1-\delta)F}_{I} \underbrace{-\delta \int_0^{\Delta c} F\, d\Phi(G)}_{II} \underbrace{+\delta \int_{\Delta c}^{\Delta c+F} (C_S - c - F)\, d\Phi(G)}_{III} > 0. \tag{3}$$

Proof. We derive the equilibrium by backward induction and start with the bidding equilibrium in the second stage. If the incumbent and the entrant are both present in the market, there is Bertrand price competition for selling energy to the TSO. In equilibrium, both firms submit bids equal to the marginal cost of the most expensive firm (the incumbent), and the TSO dispatches the firm with the lowest marginal cost (the entrant). The second stage operational profit of the incumbent, (i.e. profit net of investment cost) is zero, and of the entrant, it is Δc. If a single firm is present in the market, there is no competitive pressure. Without competition the incumbent has operational profit $C_S - c$, and the entrant $C_S - d$.

We now turn to the second stage investment equilibrium. First, assume that the incumbent has invested in period 1, and that the entrant decides whether to invest in period 2. Note that at the start of period 2, the realization of G is common knowledge. The entrant's decision is straightforward, it invests whenever operational profit outweighs investment costs $\Delta c > G$. The (expected) profit of the incumbent when it invests in the first stage is therefore equal to

$$\Pi_{NP}^{Invest} = (\mu - F) + \delta \int_{\Delta c}^{\overline{G}} (C_S - c)\, d\Phi(G),$$

the sum of first period profit and the expected second period operational profit. As operational profits are zero whenever $G < \Delta c$, the lower bound of the integral is Δc. Second, assume that the incumbent has not invested in period 1, and that the entrant and the incumbent simultaneously decide whether to enter and invest in period 2. Depending on the realization of G this game may have several equilibria. For $G < \Delta c$, investment is a dominant strategy for the entrant and the incumbent will not invest. For higher investment costs ($G > \Delta c$) the game is similar to a "game of chicken", with two pure Nash equilibria in which only one firm invests. We assume that in those cases, the firms coordinate on the Nash equilibrium which gives the highest social surplus.[16] Hence the entrant invests when $G < F + \Delta c$ and the incumbent when $G > F + \Delta c$ in which case it makes a profit $(C_S - c - F)$. The (expected) profit of the incumbent when it delays investment is equal to

$$\Pi_{NP}^{Wait} = \delta \int_{\Delta c + F}^{\bar{G}} (C_S - c - F) d\Phi(G).$$

The incumbent will invest in stage one if it is profitable to do so: $\Delta\Pi_{NP} = \Pi_{NP}^{Invest} - \Pi_{NP}^{Wait} > 0$, which simplifies to (3). □

Term I of Equation (3) corresponds as in the social planning condition (2) to the benefit of early investment. The term II refers to the real option value of giving up flexibility by investing early, while term III is the first mover advantage of the incumbent. Note that term II is negative, while term III is positive. By comparing conditions (2) and (3) we

[16] The game of chicken has equilibria which do not maximize total surplus. Here, we make the most favorable assumption for nodal pricing to be an efficient form of access regulation, by assuming socially optimal coordination.

see that private incentives for investment in period 1 are higher than the social incentives and that the incumbent over-invests. The over-investment of the incumbent is the result of two factors. Firstly, the incumbent has lower real option value than the social planner. Secondly, by investing first the incumbent receives an additional first-mover benefit as it appears more competitive in the resulting entry and Bertrand stages of the second period. Indeed, the first mover exerts a negative externality on the follower which is internalized by the social planner but not by the first mover.

To correct the private incentives for investment and induce the incumbent to behave according to the social optimum it is necessary to impose an investment tax T_{NP} on the incumbent in period 1.

Proposition 3. *Nodal pricing will lead to socially optimal investment levels if the incumbent pays a first period investment tax* T_{NP} *:*

$$T_{NP} = \delta \int_{\Delta c}^{\Delta c+F} (C_S - d - G)\, d\Phi(G). \tag{4}$$

This tax is equal to the expected negative externality that early investment imposes on the entrant minus the positive externality for the TSO.

Proof. The optimal size of the tax should equal the difference between the private and the social incentives for investment in period 1, $T_{NP} = \Delta\Pi_{NP} - \Delta V_{SP}$. This simplifies to 4. We now show that this tax level is equal to the expected net externality that early investment imposes on the entrant and the TSO.

If the incumbent invests in period 1, the TSO will collect a merchandising surplus $(C_s - c)$ whenever $G < \Delta c$, as firms will compete for transmission access. If the incumbent delays investments, the TSO will not collect merchandising surplus. Hence, early investments creates a positive externality for the TSO:

$$\Delta TSO_{NP} = TSO_{NP}^{Invest} - TSO_{NP}^{Wait} = \delta \int_0^{\Delta c} (C_s - c) d\Phi(G) - 0 > 0.$$

If the incumbent invests in period 1, the entrant will invest whenever $G < \Delta c$, and make an operational profit $(\Delta c - G)$. If the incumbent delays investments, the entrant will invest more often (whenever $G < \Delta c + F$) for a higher operational profit $(C_S - d - G)$. Early investments therefore creates a negative externality for the entrant:

$$\Delta E_{NP} = E_{NP}^{Invest} - E_{NP}^{Wait} = \delta \int_0^{\Delta c} (\Delta c - G)\, d\Phi(G) - \delta \int_0^{\Delta c+F} (C_S - d - G) d\Phi(G) < 0.$$

The social optimal investment tax is equal to the total expected externality $T_{NP} = \Delta TSO_{NP} + \Delta E_{NP}$. □

Note that the regulator should commit to a particular investment tax policy before the realization of the entrant's fixed cost G. This implies that the optimal tax can only be implemented if the regulator has as good information as the incumbent on the distribution of the stochastic fixed cost G of the entrant.

3.2 Nodal Pricing with Financial Property Rights

This section extends the nodal pricing model with financial transmission rights (FTRs). The holder of the rights receives the congestion rents if the transmission line is congested. We first derive the investment and bidding equilibrium assuming that the incumbent owns the financial transmission rights (grandfathering). Then we allow the entrant and the incumbent to bid for the transmission rights at the start of the game (auctioning) and lastly we look at grandfathering with a secondary market.

3.2.1 Grandfathering

When the incumbent holds financial transmission rights, it is not in the position to block the investment of the entrant in the second period, as the right is purely financial. However, in the cases that the entrant is more efficient and enters the market, the incumbent receives in equilibrium a compensation that equals the profit it forgoes (due to the investment of the entrant).

Proposition 4. *If the incumbent holds long-term financial transmission rights, the incumbent will always invest early.*

Proof. The bidding game in the second stage is not standard Bertrand as the incumbent is insured against paying congestion charges and therefore has a non-standard objective function. On top of operational profits, it receives payments whenever the transmission line is congested. However, it can be shown that second stage equilibrium bidding strategies are still Betrand-like.[17] If both firms are present in the market, the incumbent and the entrant both bid a price equal to the incumbent's marginal cost and the entrant is dispatched. The incumbent receives a payment $(C_S - c)$ from its FTRs and the entrant an operational profit (Δc). If the incumbent is alone in the market, it will always obtain an operational and financial profit equal to $C_s - c$.[18] If the entrant is alone in the market, it will make a (per-unit) operational profit $C_s - d$.

We now turn to the entry decisions of the second stage. If the incumbent did invest in the first stage, the entrant will invest in the second stage whenever $G < \Delta c$ (as under the nodal pricing model). If the incumbent did not yet invest in the first stage, the incumbent and the entrant simultaneously decide whether to invest in period 2. By not investing in the second stage, the incumbent will make zero profit, as it will have no operational

[17] If both firms are present, the price in the North is equal to the lowest of the incumbent's bid b_I and the entrant's bid b_E, i.e. $P_N = \min\{b_I, b_E\}$, and the firm with the lowest bid will be dispatched. The incumbent's (per-unit) financial and operational profits are equal $(C_S - P_N)$ and $(P_N - c)\, x_I$ respectively, where $x_I = 1$ if the incumbent is dispatched $(b_I < b_E)$ and zero otherwise. The operational profits of the entrant are $(P_N - d)\, x_E$, where $x_E = 1$ if the entrant is dispatched $(b_E \leq b_I)$ and zero otherwise. The entrant will undercut the bid b_I of the incumbent, as long as the bid is above its marginal cost $b_I > d$. The incumbent will undercut the entrant as long at the entrant's bid $b_E > c$. The intersection of the reaction functions is the Nash equilibrium.

[18] If the incumbent submits a bid b_I, it will obtain a financial profit $(C_S - b_I)$ and an operational profit $(b_I - c)$. Hence the incumbent's profit is independent of its bidding strategy b_I.

profit and will not collect any financial payments either, by lack of competition for the transmission line. Investing in the second stage is therefore a dominant strategy for the incumbent which guarantees a second stage profit $\delta(C_S - c - F)$. Given the dominant strategy of the incumbent, the entrant invests whenever $G < \Delta c$.[19]

As investing in the second period is a dominant strategy for the incumbent, independent of the realization of G, the incumbent will invest in period 1, as it generates an additional profit[20]

$$\Delta\Pi_{FTR\to I} = \mu - (1-\delta)F, \tag{5}$$

while the irreversibility of investments does not come at a cost. □

Comparing the investment incentives under nodal pricing in expression (3) and nodal pricing with financial transmission rights in expression (5) we observe the following: (a) The real option value of giving up flexibility by investing in period 1 disappears, as investment levels in the second period are independent of the realization of G, hence, there is no need to remain flexible. Roughly speaking the financial transmission rights provide an insurance to the incumbent against competition by an efficient entrant.[21] (b) The term corresponding to the first mover advantage disappears, because the incumbent is committed to invest in the second period (even if it did not invest in period 1) by owning a financial transmission right. This commitment effect works as follows: If the incumbent would not invest in the second period, the financial transmission rights would not generate a financial surplus (as there would be no competition for using the transmission line). Hence, the incumbent enters to increase the value of the financial transmission rights.

The addition of financial transmission rights weakly lowers total welfare, as the incumbent always invests, while it would be optimal to delay investment for some parameter ranges. Investment taxes can be used to obtain the first best also in this setting.[22]

Proposition 5. *In order to correct the investment decisions in the nodal pricing model with financial transmission rights grandfathered to the incumbent, an investment tax needs to be imposed on the incumbent both in the first* and *in the second stage.*

Proof. If the incumbent did not invest in the first stage, it should invest in the second stage (from a social viewpoint) whenever $\Delta c + F < G$. However, because of the FTRs, it will always invest in the second stage. In order to correct the second stage incentives the incumbent should pay tax $T^2_{FTR\to I}(G)$ (conditional on not investing in period 1) which

[19] Note that in the subgame where the incumbent did not invest in period 1, the investment equilibrium is not efficient as the incumbent enters too often.

[20] If the incumbent does not invest in period 1, it will have an expected profit $\Pi^{Wait}_{FTR\to I} = \delta(C_S - c - F)$, while early investments generates a profit $\Pi^{Invest}_{FTR\to I} = \mu - F + \delta(C_S - c)$. Note that the profits of the incumbent are independent of G as the FTRs provide perfect insurance.

[21] If incumbent enters in period 1, the entrant enters in period 2, then the entrant and the incumbent will compete, and drive up the price for transmission, but the incumbent will receive a financial compensation for this.

[22] Note that the incumbent receives all the congestion rents on the transmission line through the financial transmission rights. Hence investments decisions no longer create an externality for the TSO, and only externalities with respect to the entrant have to be considered.

is prohibitively high, whenever the innovative technology is efficient. For instance for any $\hat{T} \geq C_S - c - F$ the following taxation scheme implements socially optimal second stage investment:

$$T^{Period2}_{FTR \to I}(G) = \begin{cases} \hat{T} & \text{if } G < F + \Delta c, \\ 0 & \text{otherwise.} \end{cases}$$

As the second stage tax affects the second stage investment equilibrium, it also affects, by backward induction, first stage investment decisions. We indicate the first stage continuation pay-offs with a star-subscript. By investing early, the incumbent is guaranteed to obtain $C_S - c$ in the second period independent of the realization of G. Hence profits are equal to $\Pi^{Invest}_{FTR*} = (\mu - F) + \delta(C_S - c)$. By delaying investments, the incumbent receives an expected profit equal to: $\Pi^{Wait}_{FTR*} = \delta \int_{\Delta c + F}^{\bar{G}} (C_S - c - F) d\Phi(G)$ as, given the second stage investment tax, it will only invest whenever G is sufficiently high. In order to correct the investment decisions in stage 1, an expected investment tax can be imposed on the incumbent equal to:

$$\begin{aligned} T^{Period1}_{FTR \to I} &= (\Pi^{Invest}_{FTR*} - \Pi^{Wait}_{FTR*}) - \Delta V_{SP} \\ &= \delta \int_0^{\Delta c} (C_S - c) d\Phi(G) + \delta \int_{\Delta c}^{\Delta c + F} (C_S - d - G) d\Phi(G). \end{aligned} \quad (6)$$

□

Note that we need *two* instruments to correct the incentives of the incumbent, one for each investment period. As the FTRs insure the incumbent against entry, the incumbent will, ex-post, never regret its investment decisions in the first stage, and hence the real option value is zero. The first period tax internalizes the real option value. The FTR only has a positive value if there is competition in the market. So even if there is no distortion in the first stage, the incumbent always has the incentive to invest in the second period. This is not socially optimal. The second period tax corrects for this incentive.

3.2.2 Auctioning

We now consider a well functioning primary market in which the FTRs are sold through an efficient auction before period 1 and both the entrant and the incumbent submit bids. We study the incentives of both players to buy the FTRs. This implies that we need to compare their payoffs when they hold and do not hold the FTRs. We first derive the market outcome if the entrant obtains all the financial transmission rights, then we look at the bidding process in the first stage.

If the entrant owns the FTRs before period 1, then, it is fully compensated for not producing in the second period. As the FTRs provide insurance, it now becomes a dominant strategy for the entrant to always enter the market, whatever the actions of the incumbent are. The equilibrium is described by the following proposition:

	Profit Entrant	Profit Incumbent
FTRs to Entrant	$E_{FTR\to E} = \delta \int (C_S - d - G) d\Phi(G)$	$\Pi_{FTR\to E} = 0$
FTRs to Incumbent	$E_{FTR\to I} = \delta \int_0^{\Delta c} (\Delta c - G) d\Phi(G)$	$\Pi_{FTR\to I} = (\mu - F) + \delta(C_S - c)$

Table 1: Continuation pay-offs of the FTR auction.

Proposition 6. *If the entrant is the holder of FTRs, it always enters the market in period 2 while the incumbent will never invest.*

Proof. As in proposition 4 we can derive the bidding equilibrium in the second stage. If both firms are present, the entrant will always underbid the incumbent and obtain a total profit equal to $C_S - d - G$. The incumbent will make zero profit as it is more expensive than the entrant. If only the incumbent is present, it obtains an operational profit $C_s - c$, while the entrant has zero profit (as the FTRs do not generate a payment). If the entrant is alone in the market it obtains a profit $C_s - d - G$. Turning to the investment equilibrium in the second stage, we observe that it is a dominant strategy for the entrant to invest independent of the realization of G. Hence, the incumbent will never make any operational profit in the second stage, which also makes investment in stage 1 not worthwhile (as we assume that first period profits are insufficient to pay the investment costs $\mu < F$). By investing early the incumbent makes a negative profit $\Pi^{Invest}_{FTR\to E} = (\mu - F) < 0$. So, it never invests.[23] □

We are now ready to derive the market equilibrium in the bidding game for financial transmission rights:

Proposition 7. *If the incumbent and the entrant bid for financial transmission rights in period 1, then the incumbent will outbid the entrant, obtain the financial transmission rights and invest early whenever*

$$\Delta V_{SP} + \delta \int_{\Delta c + F}^{\overline{G}} (G - \Delta c - F) d\Phi(G) > 0. \tag{7}$$

Hence, the incumbent invests early more often than in the social optimum.

Proof. Table (1) reports the continuation pay-offs of the FTR auction, i.e. the expected profits of obtaining and not obtaining the financial transmission rights for the incumbent and the entrant.

The incumbent will outbid the entrant for the FTRs, (in which case it will invest early) whenever $E_{FTR\to E} - E_{FTR\to I} < \Pi_{FTR\to I} - \Pi_{FTR\to E}$. Hence both the incumbent and the entrant take into account the preemption effect of owning the transmission lines. This condition simplifies to Equation 7. □

[23] Late entry by the incumbent is never profitable given the assumption that the incumbent has a higher marginal cost than the entrant.

a. Incumbent did not invest in period 1	Profit Entrant	Profit Incumbent
FTRs to Entrant	$E_{FTR\to E} = \delta(C_S - d - G)$	$\Pi_{FTR\to E} = 0$
FTRs to Incumbent	$E_{FTR\to I} = \delta \max\{\Delta c - G, 0\}$	$\Pi_{FTR\to I} = \delta(C_S - c - F)$

b. Incumbent invested in period 1	Profit Entrant	Profit Incumbent
FTRs to Entrant	$E_{FTR\to E} = \delta(C_s - d - G)$	$\Pi_{FTR\to E} = \mu - F$
FTRs to Incumbent	$E_{FTR\to I} = \delta \max\{\Delta c - G, 0\}$	$\Pi_{FTR\to I} = (\mu - F) + \delta(C_S - c)$

Table 2: Continuation pay-offs of the FTR secondary market conditional on the incumbent investing in period 1 (top) or not (bottom).

The bidding equilibrium between the firms ensures that the allocation of FTRs is such that the highest total surplus is generated in the continuation game, i.e. the allocation is efficient.[24] However, efficient allocation in the first period cannot avoid inefficiencies in the second period. Whenever the entrant buys the FTRs, it will invest in the period 2 for sure, and the incumbent will not invest at all. However, conditional on the incumbent not investing in period 1, this investment decision may not be efficient. Indeed, it would be socially optimal for the entrant not to invest in period 2 when the entrant has high investment costs: $G > F + \Delta c$. Compared with the social optimal outcome, delaying investments (by allocating the FTRs to the entrant) leads to an additional expected cost $\delta \int_{\Delta c+F}^{\overline{G}} (G - \Delta c - F) d\Phi(G)$. This additional cost makes the incumbent more likely to win the bidding game than in the social optimum, as expressed by Equation 7.

By imposing an investment tax $T = \delta \int_{\Delta c+F}^{\overline{G}} (G + \Delta c - F) d\Phi(G)$ on early investment by the incumbent, the incumbent's investment decisions will be the same as in the first best. However, without any other policies affecting second stage investment decisions, the tax will lower total welfare as there will be more inefficient entry by expensive entrants.[25]

3.2.3 Grandfathering with secondary market

Thus far we assumed that the incumbent is unable to resell the financial transmission rights that were grandfathered to it. By adding a secondary market for transmission rights in the beginning of stage two this assumption is relaxed. After the realization of the fixed cost G, the holder of FTRs can make a take-it-or-leave-it offer to its competitor for reselling the FTRs.

Proposition 8. *If the incumbent has all bargaining power in the secondary market, grand-*

[24] The bidding condition $E_{FTR\to E} - E_{FTR\to I} < \Pi_{FTR\to I} - \Pi_{FTR\to E}$ is equivalent to $E_{FTR\to E} + \Pi_{FTR\to E} < E_{FTR\to I} + \Pi_{FTR\to I}$. Note that with FTRs the network operator is not allowed to keep any congestion revenues, and hence there are no externalities with respect to third parties.

[25] More precisely, it lowers total welfare for the range of parameters where investment decisions are affected by the tax.

fathering FTRs to the incumbent is socially efficient.

Proof. We solve the game by backward induction. First, suppose that the incumbent has not yet invested in period 1, then the continuation pay-offs in the secondary market are given by Table 2.a. The incumbent will resell the FTRs to the entrant whenever $E_{FTR\to E} - E_{FTR\to I} > \Pi_{FTR\to I}$, which simplifies to $G < \Delta c + F$. Hence second period efficiency is restored. If the incumbent has all bargaining power and makes a take-it-or-leave-it offer, it will receive a payment P from the entrant:[26]

$$P = \begin{cases} \delta(C_s - c) & \text{if } G < \Delta c, \\ \delta(C_s - d - G) & \text{if } F + \Delta c > G > \Delta c, \\ \text{no trade} & \text{otherwise.} \end{cases}$$

Second, suppose the incumbent has already invested in stage 1, then the continuation pay-offs are given by Table 2.b. The incumbent will resell the FTRs to the entrant whenever $E_{FTR\to E} - E_{FTR\to I} > \Pi_{FTR\to I}$. When the entrant has high investment costs $G > \Delta c$ trade will not take place. When they are low, $G \leq \Delta c$, there are no gains from trade, and the firms are indifferent between trading and not trading.

Including the resale value P of the financial transmission rights and with early investment, the incumbent obtains profit:

$$\Pi^{Invest}_{FTR\to I} = (\mu - F) + \delta(C_S - c),$$

and with delayed investments:

$$\begin{aligned} \Pi^{Wait}_{FTR\to I} &= \delta(C_S - c - F) + \delta \int_0^{\Delta c} (C_S - c) - (C_S - c - F)\, d\Phi(G) \\ &+ \delta \int_{\Delta c}^{\Delta c + F} (C_S - d - G) - (C_S - c - F)\, d\Phi(G). \end{aligned} \tag{8}$$

where the second and the third term include the resale value of the FTRs.

The incumbent will invest in period 1 whenever

$$\Delta\Pi^{Secondary}_{FTR\to I} = \Pi^{Invest}_{FTR\to I} - \Pi^{Wait}_{FTR\to I} = \Delta V_{SP} \geq 0,$$

which is identical to the social planner's outcome in equation 2.

The existence of the secondary market makes the incumbent to internalize the impact of its first period's investment investment decision on the entrant's expected profit. Hence, private and social incentives coincide through the potential trade of the rights at the secondary market at a price decided by the incumbent. □

Note that if the FTRs are auctioned before period 1 instead of being grandfathered, then the incumbent weakly outbids the entrant. Hence, both an auction and/or grandfathering of the rights to the incumbent leads to the same efficient outcome.[27]

[26] Assuming that the entrant would have all the bargaining power the price would be: $P = C_S - c - F$. Trade would take place whenever $G < \Delta c + F$.

[27] Note that the payoffs of the entrant when the incumbent is the holder of the rights are $E^{Invset}_{FTR\to I} =$

3.3 Physical Property Rights

This section present the market equilibrium with a physical property rights approach, an alternative to nodal pricing with financial transmission rights. Although not practically implementable in the power market, those results provide a useful benchmark. The physical property rights are assumed to be grandfathered to the incumbent in stage 1, and offered by the incumbent with a take-it-or-leave-it offer on a secondary market in the beginning of period 2.[28]

Proposition 9. *In a model with Physical Transmission Rights with a secondary market, investments levels are efficient.*

Proof. First, suppose that the incumbent invests in stage 1. It will resell the PTRs to the entrant for a payment equal $\delta(C_s-d-G)$ if this payment is larger than the profit obtained by holding to the PTR, $\delta(C_s-c)$. Hence trade will take place and the entrant invests whenever it is socially optimal ($G<\Delta c$). The profit of the incumbent for investing early is equal to

$$\Pi^{Invest}_{PTR\to I} = \mu - F + \delta\int_0^{\Delta c}(C_S-d-G)d\Phi(G) + \delta\int_{\Delta c}^{\bar{G}}(C_S-c)d\Phi(G).$$

Second, suppose that the incumbent did not invest in stage 1. Now it will resell the PTRs to the entrant for a payment equal to $\delta(C_s-d-G)$ if this payment is larger than the profit of holding on to the PRT, $\delta(C_s-c-F)$. Trade takes place whenever $G<\Delta c+F$. The profit of the incumbent is equal to

$$\Pi^{Wait}_{PTR\to I} = \delta\int_0^{\Delta c+F}(C_S-d-G)d\Phi(G) + \delta\int_{\Delta c+F}^{\bar{G}}(C_S-c-F)d\Phi(G).$$

The incumbent invests early if $\Delta\Pi_{PTR\to I} = \Pi^{Invest}_{PTR\to I} - \Pi^{Wait}_{PTR\to I} = \Delta V_{SP} \geq 0$, which is equal to the first best investment level.

The incumbent as a holder of PTRs fully internalizes the impact of its early investment to the entrant. Again this occurs through the secondary market and the resale of the rights to the entrant when the latter is efficient and enters the market. □

$E^{Wait}_{FTR\to I} = \delta\int_0^{\Delta c}(\Delta c-G)d\Phi(G)$. When the entrant is the holder of the rights (with full bargaining power in the secondary market), the incumbent never invests in period 1 as it expects to have zero profit in the second period and therefore it is unable to cover the sunk cost of the investment. Therefore the relevant payoff for the entrant in this case is: $E^{Wait}_{FTR\to E} = \delta(C_S-d-G) + \delta\int_{\Delta c}^{\overline{G}}(G-\Delta c)d\Phi(G)$, while for the incumbent we have $\Pi^{Wait}_{FTR\to E}=0$. Whenever, $\Pi^{Invest}_{FTR\to I} < \Pi^{Wait}_{FTR\to I}$, both the incumbent and the entrant have the same valuations for the rights and submit equal bids: $E^{Wait}_{FTR\to E} - E^{Wait}_{FTR\to I} = \Pi^{Wait}_{FTR\to I} - \Pi^{Wait}_{FTR\to E}$. When $\Pi^{Invest}_{FTR\to I} > \Pi^{Wait}_{FTR\to I}$, the incumbent outbids the entrant and gets the rights: $E^{Wait}_{FTR\to E} - E^{Invest}_{FTR\to I} < \Pi^{Invest}_{FTR\to I} - \Pi^{Wait}_{FTR\to E}$.

[28] If the rights would be auctioned in stage 1, the incumbent would (weakly) outbid the entrant, as it has additional benefits from accessing the transmission line in period one. Therefore the results derived in this section would remain valid.

Note that if the PTRs are sold initially through an auction, then the incumbent weakly outbids the entrant and gets the rights, so, grandfathering the rights to the incumbent or selling them through an efficient auction is equivalent for achieving the socially efficient outcome.[29]

4 Surplus sharing in secondary market

4.1 Grandfathering with secondary market

So far we assumed that the incumbent, could make a take-it-or-leave-it offer in the secondary market, and, therefore, had all bargaining power and internalized the full real option value. If instead the incumbent leaves a fraction $\beta \in [0,1]$ of the gains from trade in the secondary market to the entrant, it internalizes less, and is more likely to invest early.[30] In particular, with interim trade and grandfathering of transmission rights, the incumbent will invest early in period 1 when

$$\Delta\Pi_{TR} = \underbrace{\mu - (1-\delta)F}_{I} - (1-\beta)\delta \underbrace{\left[\int_0^{\Delta c} F \, d\Phi(G) + \int_{\Delta c}^{\Delta c + F} (F + \Delta c - G) \, d\Phi(G)\right]}_{II}.$$

independent whether trading FTRs or PTRs. Note that for $\beta = 0$ this expressions converges to the first best and for $\beta = 1$ to the grandfathered FTRs without a secondary market. With less bargaining power, the incumbent will invest early more often.

Comparing this expression with the investment under nodal pricing without financial transmission rights (equation 3), one can determine in which cases transmission rights (with secondary market) might improve investment efficiency. In both situations, the incumbent might invest too early, but for different reasons: Under nodal pricing, overinvestment is due to a first mover advantage, and not fully internalizing the real option value for intermediate cost realizations ($\Delta c < G < \Delta c + F$). This size of the distortion is determined by the investment externality

$$\int_{\Delta c}^{\Delta c + F} (C_S - d - G) \, d\Phi(G). \tag{9}$$

With a secondary market for financial transmission rights without full bargaining power for the incumbent, only a fraction $1 - \beta$ of the real option value is captured by the incumbent. The distortion is then equal to

$$\beta \left[\int_0^{\Delta c} F \, d\Phi(G) + \int_{\Delta c}^{\Delta c + F} (F + \Delta c - G) \, d\Phi(G)\right]. \tag{10}$$

[29] Note that when the entrant is the holder of the PTRs the incumbent never invests in period 1. Moreover, it is $\Pi^{Wait}_{PTR\to I} = E^{Wait}_{PTR\to E}$, so when the incumbent does not invest early, it has the same valuation with the entrant for the rights. Whenever, investment in period 1 is socially optimal, we have $\Pi^{Invest}_{PTR\to I} > \Pi^{Wait}_{PTR\to I}$ and therefore, the incumbent weakly outbids the entrant.

[30] Surplus sharing requires bargaining between the two generators over the price of the rights. We focus on the case that bargaining is efficient ex-post and the outcome lies on the Pareto frontier.

We can combine both expressions to determine when financial transmission rights are welfare improving.[31] If the incumbent captures only a small fraction of the value of trade, that is β is larger than a critical value $\hat{\beta}$

$$\beta > \widehat{\beta} = \frac{\int_{\Delta c}^{\Delta c+F} (C_S - d - G)\, d\Phi(G)}{\int_0^{\Delta c} F\, d\Phi(G) + \int_{\Delta c}^{\Delta c+F} (F + \Delta c - G)\, d\Phi(G)},$$

then introducing transmission rights will reduce welfare as the second distortion will outweigh the first one.

By rewriting the expression for $\hat{\beta}$ one can derive that a critical value $\widehat{\beta} \leq 1$ exists if the first mover advantage $C_S - c - F$ under nodal pricing (i.e. deterring entry when G is intermediate) is smaller than the sunk cost F when the entry cannot be deterred because the entrant is too efficient ($G < \Delta c$):

$$\int_{\Delta c}^{\Delta c+F} (C_S - c - F)\, d\Phi(G) < \int_0^{\Delta c} F\, d\Phi(G).$$

Hence, financial transmission rights will increase welfare for sure if the production cost difference is small ($\Delta c \to 0$), the equilibrium price in the South C_S is large and production cost of the entrant are likely to be intermediate (higher first mover advantage).

4.2 Auctioning

In this partial bargaining power analysis, we have assumed so far that the rights are grandfathered to the incumbent and we concluded that the incumbent overinvests. If instead we have an efficient auction for the rights which takes place before period 1 and in which both the incumbent and the entrant participate, the welfare increases as private incentives for investment coincide with the social ones. So, an auction leads to a more efficient outcome than grandfathering when we drop off the assumption of the take-it-or-leave-it offer in the secondary market.

Proposition 10. *If the holder of long term transmission rights (either financial or physical) has only partial bargaining power in the secondary market, auctioning the rights in the primary market leads to socially efficient investment levels.*

Proof. The incumbent will outbid the entrant in the primary auction for the FTRs when his valuation for obtaining the rights, $\Pi_{FTR\to I} - \Pi_{FTR\to E}$, is larger than the entrant's valuation $E_{FTR\to E} - E_{FTR\to I}$, where Π and E are the continuation pay-offs for the incumbent and the entrant respectively. This implies that the incumbent will buy the property rights if and only if allocating the rights to the incumbent creates a larger joint expected continuation surplus than allocating them to the entrant, $\Pi_{FTR\to I} + E_{FTR\to I} > \Pi_{FTR\to E} + E_{FTR\to E}$. Note that as the network operator does not obtain any congestion rents once the transmission

[31] Conditional on first stage entry, second stage investment decisions are optimal in both situations. Hence we only need to compare first period investment decisions.

rights are allocated, the joint continuation surplus of the incumbent and the entrant is equal to total social surplus in the continuation game. The negotiation in the secondary market for the property rights is ex-post efficient. This means, that *conditional on the incumbent's investment* decision in stage 1, the incumbent and the entrant will maximize their joint surplus $\Pi + E$ when they trade in the secondary market, and decide about their investments. The joint surplus of the continuation game is given by the following expression:

$$\Pi + E = \begin{cases} (\mu - F) + \delta\left(C_S - c + \int_0^{\Delta c}(\Delta c - G)d\Phi(G)\right) & \text{if } I \text{ invests,} \\ \delta\left[\int_0^{\Delta c+F}(C_S - d - G)\,d\Phi(G) + \int_{\Delta c+F}^{\bar{G}}(C_S - c - F)d\Phi(G)\right] & \text{if } I \text{ waits.} \end{cases} \tag{11}$$

The incumbent and the entrant will obtain each a share of this joint surplus. The size of their share depends on the bargaining factor β and on the allocation of the property rights in the primary stage. Total surplus $\Pi + E$ would be maximized if the incumbent would invest whenever the $\Delta V_{SP} > 0$. Any deviation from the socially optimal investment rule will lead to a lower level of total surplus. As the incumbent does not fully internalize the entrant's profits, it only takes into account private investment incentives $\Delta\Pi = \Pi^{Invest} - \Pi^{Wait}$ and investments are therefore socially sub-optimal. It can be shown that for any level of intermediate bargaining $\beta \in (0,1)$, the incumbent will invest more than socially optimal if the incumbent obtained the rights in the primary market, and less than socially optimal if the entrant obtained those rights. That is the incumbent's investment incentives are ranked as follows:

$$\Delta\Pi_{FTR\to I} > \Delta V_{SP} > \Delta\Pi_{FTR\to E}.$$

We can now check the following four situations, which could be depending on the parameters of the game could occur:

1. $\Delta\Pi_{FTR\to I} > \Delta V_{SP} > \Delta\Pi_{FTR\to E} > 0$. The incumbent will invest early, independent of the allocation of the FTRs. Hence, the Incumbent and the Entrant have identical valuation for the FTRs, as total surplus $\Pi + E$ is the same. In the primary market they obtain the right with 50% probability.

2. $\Delta\Pi_{FTR\to I} > \Delta V_{SP} > 0 > \Delta\Pi_{FTR\to E}$. The incumbent will only invest early if it obtained the property rights in the primary market. Early investment is socially optimal ($\Delta V_{SP} > 0$) and hence total market surplus $\Pi + E$ is maximized if the incumbent obtains the rights. As the auction in the first stage allocate the FTR such that the joint continuation payoff is maximized, the incumbent will obtain the rights, and the outcome is socially efficient.

3. $\Delta\Pi_{FTR\to I} > 0 > \Delta V_{SP} > \Delta\Pi_{FTR\to E}$. The incumbent will only invest early if it obtains the property rights. It is socially optimal to wait, hence total surplus is higher in case the rights are allocated to the entrant, and therefore the entrant will outbid the incumbent. In equilibrium the incumbent will wait, and the outcome is socially efficient.

4. $0 > \Delta\Pi_{FTR\to I} > \Delta V_{SP} > \Delta\Pi_{FTR\to E}$. The incumbent will always wait to invest in the first period independent of the allocation of the FTRs. This is also socially optimal. The incumbent and the entrant will have identical valuations for the property rights, and in the primary market they both have a 50% probability for obtaining the property FTRs.

Hence in all four cases, total surplus is maximized. For physical transmission rights the proof is analogue. □

The competitive initial allocation of the long-term transmission rights guarantees efficiency, independent of how the trading surplus in the secondary market is shared between the seller and the buyer of the rights. Hence, a combination of a competitive initial allocation with a well functioning secondary market leads to an efficient outcome. Auctioning the initial rights is (weakly) preferred to grandfathering to the incumbent as it generates a higher surplus if the incumbent cannot extract the full trading surplus.

5 Conclusions

We study the dynamic efficiency of several types of access regulation of a bottleneck transmission line in electricity markets. The current practice of organizing short-term markets for those bottlenecks, leads to premature investments by brown incumbent generators because they want to exploit their first-mover advantage. We show that long-term transmission rights may restore dynamic efficiency. However, this always requires the presence of a secondary market. Without one, the situation will actually be worse than without long-term rights. Investments are efficient in two situations. (1) The brown incumbent has full bargaining power in the secondary market: In that case the incumbent fully internalizes the effects of its investment timing on the entrant's pay-off. (2) The initial allocation of the property rights is competitive and the entrant is an active bidder in the primary market. This would require that the green entrant has sufficient information about the evolution of future investment costs.[32]

Instead of introducing long-term property rights, regulators could, in theory, restore efficiency by imposing an investment tax on early investment by the incumbent. In order to determine the optimal tax level, the regulator would require information about the likelihood that the investment costs of the green entrant are of intermediate value. We do not believe that this information is readily available, and therefore we prefer the introduction of long-term property rights to taxation instruments. To implement this mechanism, regulators can choose between financial and physical transmission rights. We show that efficiency is achieved with both types of rights. However, as financial rights do not raise concerns regarding strategic withholding of transmission capacity (Joskow and Tirole, 2000), they

[32]There is some anecdotal evidence that green energy companies in Belgium were sufficiently forward looking as to sign exclusivity agreements with land owners in good wind locations (high wind speeds, close to the grid, and away from nature reserves and residential areas) many years before actually building any wind turbine.

are our the preferred option. Note that long-term property rights have additional benefits which were not explicitly considered in this paper: They allow risk-averse firms to hedge risks, and provide additional information about the value of network expansion to the network operator.

We study a market in which local pockets with market power supply energy to a large competitive market. Competitive pricing is a reasonable assumption for the long-term equilibrium of a large liberalized market without significant entry barriers. Obviously, with an additional market failure (market power in the South), the relative efficiency of scenarios will change. Early investments in the North will limit market power abuse in the South and increase allocative efficiency.[33] However, persistent problems of market power should be solved by policies that address them directly (for instance structural and behavioral remedies such as divestitures and bid caps) and not indirectly by network access regulation. Modeling those additional market failures and the preferred policies is outside the scope of the paper.

[33] For instance, if there is a monopoly producer in the South, the price in the South will be $p_S^{Wait} = \arg\max(p - C_S)D(p)$, without investments in the North and $p_S^{Invest} = \arg\max(p - C_S)(D(p) - K)$ with investments. Clearly, early investment in the North aligns prices in the South to marginal cost $p_S^{Wait} > p_S^{Invest} > C_S$.

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