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# Long-term transmission rights and dynamic efficiency

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ABSTRACT

We compare market designs for access regulation of a bottleneck transmission line, and study their impact on investment decisions by an incumbent firm with an existing dirty technology and entrant with an uncertain future low-carbon technology. Nodal pricing, which allocates network access on a short-term competitive basis, distorts investment decisions, as the incumbent preempts the entrant by investing early. Long-term tradable transmission rights restore investment efficiency: the incumbent's investment timing becomes socially optimal. This is the case for financial and physical transmission rights, but it requires the existence of a secondary market for transmission rights.



## 1. Introduction

Before the liberalization of the energy sector, investments in generation capacity were coordinated centrally and network constraints were fully taken into account in a forward looking manner. Indeed, interactions between generation investments and transmission constraints are important: operating a new power plant may require existing plants to cut-back production and investments today may preempt otherwise profitable future investments. However, in a liberalized market, coordination has to take place through the market. Oxera (2003) estimates that around 80% of the benefits of locational price signals result from the long-term effect of plant siting, while only 20% comes from the short-term operational optimization of existing plants.

We focus on those long-term effects, and compare several electricity market designs for transmission access taking into account the dynamic nature of generation investments. To our knowledge we are the first to study the effect of transmission market design on generation investments in an oligopoly setting. We build a stylized model that is inspired by current power markets: a first-mover with a mature "brown" conventional production technology and second-mover with a future "green" low-carbon technology compete for accessing a transmission line and selling energy to end-users. The first-mover faces a strategic real option problem: Should it delay investments to learn more about the future cost of the green competitor, or should it invest early in order to deter entry?

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. In the second design a financial transmission right market is added to the nodal spot market. The owner of a financial transmission right (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 outcome of the short-term auction. The third design has 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 the lifetime of the incumbent's investment. They are allocated before the first stage in a primary market, either through

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grandfathering or in an auction. 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 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 for new entry by for instance grandfathering long-term non-tradable financial transmission rights to the incumbent, only exacerbates this problem: 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. Investment efficiency can be restored by allowing the resale of transmission rights. As early investment lowers the expected resale value of the transmission rights, the incumbent will delay investments to the socially optimal level. By reselling a 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, but also financial ones are efficient.

### 1.1. 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). 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.[1]

Most U.S. power markets use this nodal 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 financial transmission rights are introduced.[2] Those rights are used by market participants to manage the risk of their long term energy contracts and their power plant portfolio.[3] They could also be used to improve regulation of transmission investments as they provide information about (future) transmission service demand (Henze et al., 2012; Rosellón and Weigt, 2011). 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.[4] In our paper we study both grandfathering and a primary market auction.

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, and receive their exclusive usage. Gradually those physical transmission rights are being phased out, and in the transition phase they often receive properties that make them more alike financial rights. For instance, physical transmission rights can come with use-it-or-loose-it or use-it-or-sell-it rules, which frees up transmission capacity that remains unscheduled, so it can be used in the short term spot market.[5] We model the physical transmission right in its purest form, in which they can be used to exclude firms from using transmission capacity.[6]

For bottlenecks within a zone, European markets use a special market design called counter trading (Bjørndal et al., 2003). 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.[7] We do not explicitly model counter trading as a fourth market design, because in our setting it is equivalent to grandfathering non-tradable financial transmission rights to the incumbent. This leads to overinvestment by the incumbent.

We assume that the entrant's investment cost is unknown when the incumbent makes its first investment decision. This reflects the fact that renewable energy technologies have not yet reached maturity. Wiser et al. (2016) survey industry experts on their views on the evolution of wind energy production cost by 2050. Views are very dispersed, with the bottom 10th percentile predicting no change, and the top 90th percentile a drop of 50%. Also Irena's (2016) forecasts for production costs by 2025 show a large range of estimates (Table 1).

### 1.2. Related literature

Earlier work on *transmission market designs* and *market power* have focused only on short-run effects: how do firms bid into the spot market and who accesses the transmission line. We extend this literature by introducing *uncertainty* about the cost of technologies and by studying not only spot market operation, but also the timing of *investment* decisions.

In a monopoly model, Joskow and Tirole (2000) show that *financial transmission rights* are preferred to *physical transmission rights*, as it allows for risk hedging, without allowing the monopolist to strategically foreclose its home market by withholding transmission capacity. Note that Joskow and Tirole (2000) have a deterministic model which focuses exclusively on spot market competition and the initial trade of the transmission rights. It does not consider investments or cost uncertainty, and models the entrant as a fringe producer already present in the market. We have a duopoly, two investment opportunities, cost uncertainty, a secondary market, and spot markets over two periods. Note that in Joskow and Tirole the incumbent is located downstream of transmission line, while it is upstream in our model. Our setting corresponds

[1] Schweppe et al. (1988) are early advocates for nodal pricing. Wilson (2002) argues that such a central design is necessary for short-term operational efficiency given the large number of inter-dependencies.

[2] 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. 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.

[3] For instance, a generator with production location A might sell consumers in location B a *financial* forward contract on location B's spot price. While this contract will fully hedge consumers against spot price fluctuations in their location B, the generator will still face some basis risk. That is, the difference in spot prices in location A and B might not constant. Financial transmission rights allow the generator to hedge this basis risk.

[4] For instance in the Midwest ISO, firms receive "Auction Revenue Rights" based on their historical 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. Also PJM and the Southwest Power Pool have grandfathered transmission rights.

[5] Physical transmission rights are used extensively in Europe. For instance, physical transmission rights are traded between France, Germany, Netherlands, Belgium, England, Italy, Spain and Switzerland. The Agency for Energy Regulators (ACER, 2017) imposes the use of the use-it-or-sell-it rules for physical transmission rights in the EU, which makes them similar to financial transmission rights.

[6] Physical transmission rights with a use-it-or-sell-it rule are equivalent to financial transmission rights in Joskow and Tirole (2000) and also in our setting.

[7] The effect of regional uniform prices with *counter trading* in a competitive market is studied by Dijk and Willems (2011) and Holmberg and Lazarczyk (2015). It is shown that firms adjust their bids in the regional market to reflect profits they could obtain in subsequent counter trading markets. Hence, firms take into account their strategic position in the nodal network. If consumers are unable to participate in the counter trading market, then short-term efficiency is reduced in comparison to standard nodal pricing. Green (2007) compares zonal and nodal pricing for the England and Wales market, and shows that there are considerable welfare gains by introducing nodal pricing, and stresses distributional effects.

**Table 1**
Estimates for the range of levelized cost of electricity for individual projects in 2025. Source: IRENA (2016).

| 2015USD/MWh | 5th percentile | Median | 95th percentile |
|---|---|---|---|
| Photovoltaic | 30 | 55 | 120 |
| Onshore wind | 30 | 53 | 90 |
| Offshore wind | 80 | 110 | 150 |

to a realistic market situation where production is often located outside densely populated consumption areas.[8]

Lapuerta and Harris (2004) stress that locational signals 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 set-up of our model has similarities with Aghion and Bolton (1987). In their model an incumbent and a consumer sign an exclusive long term contract with a penalty for breach, in order to extract rents from an 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. As a result some efficient entry is deterred. Aghion and Bolton show that by contracting with a third party (the consumers), the incumbent can extract some surplus from the entrant.

In our model the incumbent faces an entrant with unknown investment costs, while production costs are known. The incumbent does not need to rely on a contract with a third party to foreclose entry as it can do so by holding on to a transmission contract. So also the entry deterrence technology differs. Furthermore, we provide the incumbent with an additional entry deterrence device not present in Aghion and Bolton: investment in generation capacity. By investing early the incumbent commits to aggressive bidding, which will deter entry. Our contribution is that we show that it is socially preferred to allow the incumbent to use the transmission contract to extract rents from the entrant, because it reduces the incumbent's reliance on preemptive investments. Those preemptive investments are socially costly, and should be avoided.

Given irreversibility of investments, the incumbent faces a real option problem in the first stage (Dixit & Pindyck, 1994). We show that strategic considerations reduce the real option value of delaying investments and create a first mover benefit for the incumbent, which 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, and leads to earlier investments. However, our setting differs as we study different transmission market designs.

Our paper is linked to two strands of property rights literature: private nuisance and government takings. The first strand 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.[9] 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 to 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).

The second strand 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 liberalize power markets, introduce regulated network access, and massively subsidize green energy, the incumbent often looses its (implicitly) guaranteed access right. The standard recipe in the literature in such a situation is *zero compensation* (Blume et al., 1984; Fischel and Shapiro, 1989): the government 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 some power markets, governments recognize those “historical access rights” by grandfathering transmission rights to the firm once it invests (see footnote 4). 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 zero compensation result no longer holds, as the effect on the resale value reduces the incentives for early investments by the incumbent, which restores efficiency. Hence, there is no longer a trade-off between equity (providing a compensation) and 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 modeling assumptions and 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 (there is no market power), but occurs at high marginal cost $C_S$. These high marginal cost reflect the fact that the South is geographically a less favorable production location.[10] 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

[8] Many studies consider short term strategic behavior under *nodal pricing*, without considering alternative market designs, and are therefore less relevant for our study. Their focus is on how network topology, transmission constraints and the location of generation assets affect market power. Wei and Smeers (1999) provide a seminal set-up for large scale computational equilibrium models. Borenstein et al. (2000) illustrate how firms can strategically congest transmission lines. Neuhoff et al. (2005) and Willems (2002) compare different approaches to model transmission constraints in Cournot models, and Holmberg and Philpott (2015) use a Supply Function Equilibrium setting instead of Cournot. Note that Gilbert, at al. (2004) extend the Joskow and Tirole (2000) model to an oligopoly setting.

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

[10] Local conditions affect production costs such as the availability and cost of land (including zoning restrictions), access to cooling water, the connection to transportation networks (rail or water), wind speed, and local regulations. North-South congestion is for instance observed in California, Italy and Norway. In those three cases this is (partially) driven by cheap hydro in the North. Congestion in the west-side of the Netherlands is driven by cheap combined heat and power plants which are used also for heating greenhouses.

production by southern generators is always necessary.[11] 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 lifespan 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.[12] 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.[13]

The incumbent and the entrant have marginal costs $c$ and $d$, and (per unit) investment 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 unknown, but it is common knowledge that it is drawn from stochastic distribution on support $[0, \bar{G}]$ with cumulative density $\Phi(G)$. 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 ($c + F < d + \bar{G} < C_S$).

Competition and investment in the North depend on transmission access regulation and the accompanying property rights regime. In what follows, we examine three 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.

Under nodal pricing, the transmission line is managed by the system operator (SO) 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. 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 system operator as scarcity rents. The nodal pricing operates as a uniform price auction. In each node a single price is determined at which all supply and demand is traded.[14]

For our topology, nodal pricing implies the following: The incumbent and the entrant compete à la Bertrand for supplying energy services in the North. The SO 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 SO 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 a financial transmission right (FTR). 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 on the holder's profit is that in case it 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. If we consider a secondary market, the holder of the rights has the option to resell them to its rival firm.

An alternative regulatory model for network access is a physical transmission right (PTR). 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 SO, 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 or grandfathered. If there is a secondary market, the holder of the rights has the option to resell them to its rival firm instead of using the line itself.

The timing of the game differs slightly between the three scenarios (Fig. 1).

- 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. Long-term transmission rights can be allocated through *grandfathering,* where the rights are given for free to the incumbent or *sold on an auction* in which the incumbent and the entrant bid for the right, and the right is allocated to the highest bidder.
- 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 $\mu$.[15]
- Between period 1 and 2, nature draws the fixed cost $G$ of the entrant. The realization of $G$ is common knowledge. If there is a *secondary market* for long-term transmission rights, following the realization of $G$, the owner of the long-term rights may sell the contract to its competitor.
- 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). In the nodal pricing and FTR scenario, firms choose their pricing behavior in the resulting Bertrand game. The SO 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.

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, $\mu$ is

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

[12] Note that wind and solar power have zero marginal production costs, as they do not burn fossil fuel. Maintenance and operating costs (for instance the cleaning of solar panels) do not depend much on the actual production output of those panels.

[13] This assumption is relaxed in Section 4.

[14] This is the market model most power exchanges use. Discriminatory auctions (also called pay-as-bid auctions) are more common in balancing markets, where the system operator often activates power plants out of merit to manage real time imbalances or grid constraints.

[15] In the nodal pricing and FTR scenario, the incumbent submits an energy bid to the SO for producing electricity. In equilibrium the SO dispatches the incumbent and the transmission lines are 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.

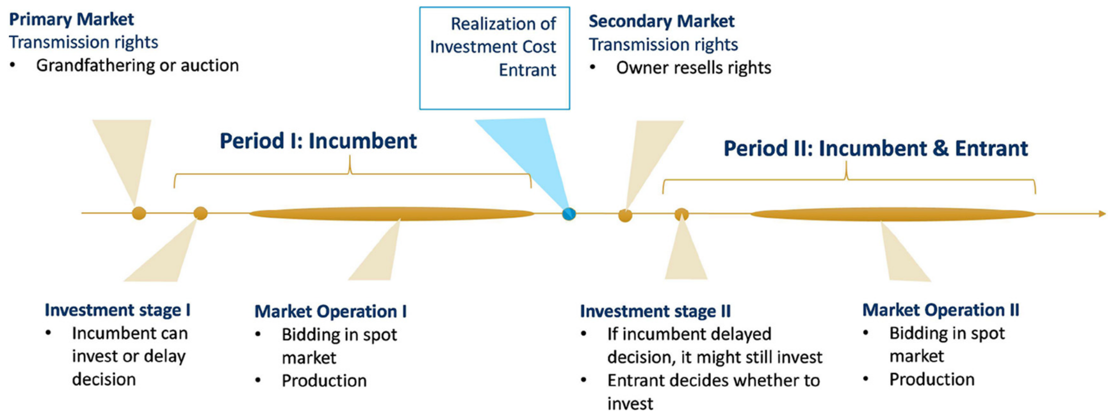


**Fig. 1.** Timing of the game.

smaller than its investment cost $F$, ($\mu < F$).[16] 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 ($\delta F$). 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. The incumbent and the entrant have symmetric information: Before period 1, they are both ignorant about the fixed cost $G$, and between period 1 and 2 they both learn the realization of $G$. If transmission rights are sold in a secondary market, we assume that the owner makes a take-it-or-leave-it offer to its rival. The game is solved by backward induction.

When the incumbent does not invest early, both firms simultaneously decide on market entry before period 2. However, the market supports only one profitable firm. In scenarios with long-term tradable property rights, the property rights function as an explicit coordination device, which, in equilibrium, prevents the duplication of fixed costs. In fact, the firm with the highest continuation profit will buy, (or hold on to) the transmission rights and enter the market. Under nodal pricing such a coordination device does not exist. Therefore, for some parameter values the game is similar to a "game of chicken", with two pure Nash equilibria in which only one firm invests, and a mixed strategy equilibrium, where each firm enters with positive probability. Some of those equilibria are inefficient as they lead to the duplication of fixed costs or have the firm with the lowest continuation value enter. We need to select one of those equilibria and assume that firms coordinate on the pure Nash equilibrium in which the firm with the highest continuation value enters. This assumption favors the nodal pricing scenario as we neglect the beneficial coordination role of transmission rights in preventing the duplication of fixed costs. Nevertheless, even in that case we do not achieve the social optimal outcome.

### 2.1. Social optimum

Before analyzing the investment strategies of the incumbent and the entrant in the three scenarios we develop the social planner's investment policy as a benchmark. 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 SO (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 the 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 $K=1$.

**Definition** (Dynamic efficiency). Investment in period 1 is socially preferred to waiting if the expected cost reduction of investing early in the mature technology, $V_{SP}^{\text{Invest}}$, minus the expected cost reduction with delayed investment decisions, $V_{SP}^{\text{Wait}}$, is positive:

$$\Delta V_{SP} = V_{SP}^{\text{Invest}} - V_{SP}^{\text{Wait}} > 0.$$

A market design is *dynamically efficient* if it leads to socially optimal investment decision in period 1 independent of the investment cost $F$ of the incumbent.

**Lemma 1.** *The social value of early investment $\Delta V_{SP}$ is*

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

**Proof**. The expected cost reduction of investing early in the mature technology as compared to producing in the South as cost $C_S$ is equal to:

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

The first term represents social value of the first period cost reduction $\mu$ 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 $C_S - d - G$. For higher cost realizations the mature technology remains in use, and the cost reduction is $C_S - c$.

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

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

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 $C_S - c - F$. Subtracting both expressions simplifies to Eq. (2). □

[16] 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 $D_2=1$. 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 social value of early investment $\Delta V_{SP}$ is the sum of three terms: Part *I* is the *net present value of an early investment*. By investing earlier, the firm generates profit $\mu$, but the investment cost is incurred earlier, so there is a cost, $(1-\delta)F$. Given Eq. (1) this term is positive. By investing early, the social planner gives up flexibility, which comes at a cost: *the social real option value of waiting* (Parts IIa and IIb).[17]

It is straightforward from Eq. (2) that early investment becomes more attractive for a higher discount rate $\delta$, higher first period profit $\mu$, and lower investments cost $F$. Note that if there 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. We look at nodal pricing first, then at financial transmission rights with and without secondary markets, and conclude with physical transmission rights with a secondary market.

### 3.1. Nodal pricing

Proposition 1 summarizes the incumbent's investment decisions in period 1 and checks whether they correspond to the social optimum.

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

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

*The incumbent invests early more often than is socially optimal.*

**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 SO. In equilibrium, both firms submit bids equal to the marginal cost of the most expensive firm (the incumbent), and the SO dispatches the firm with the lowest marginal cost (the entrant).[18] The second stage operational profit of the incumbent, (i.e. profit net of investment cost) is zero, and of the entrant, it is $\Delta c$. 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

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

the sum of first period profit and the expected second period operational profit. 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 aggregate surplus (as explained in the model section). 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

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

The incumbent will invest in stage one if it is profitable to do so: $\Delta \Pi_{NP} = \Pi_{NP}^{\text{Invest}} - \Pi_{NP}^{\text{Wait}} > 0$, which simplifies to Eq. (3). By comparing conditions (2) and (3) we see that private incentives for investment in period 1 are higher than the social incentives and that the incumbent over-invests $\Delta \Pi_{NP} \geq \Delta V_{SP}$. □

Expression 3 is the sum of three parts: term I corresponds to the *net present value of an early investment*, term II to the *real option value of giving up flexibility* by investing early, and term III to the *first mover advantage* of the incumbent.

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 early the incumbent receives an additional first-mover benefit as it becomes 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. This requires that the regulator has good information on the distribution of the entrant's fixed cost $G$.

**Lemma 2** (Pigouvian Investment Tax) *If the incumbent pays a first period investment tax $T_{NP}$*

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

*then the market equilibrium is dynamically efficient under nodal pricing. This is a Pigouvian tax equal to the expected negative externality that early investment imposes on the entrant minus the positive externality on the System Operator (SO).*

**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 Eq. (4). We now show that this tax level is equal to the expected net externality that early investment imposes on the entrant and the SO.

If the incumbent invests in period 1, the SO 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 SO will not collect merchandising surplus. Hence, early investment creates a positive externality for the SO:

$$\Delta SO_{NP} = SO_{NP}^{\text{Invest}} - SO_{NP}^{\text{Wait}} = \delta \int_0^{\Delta c} (C_S - c)\, d\Phi(G) - 0 > 0.$$

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

[17] 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 $(c + F) - (d + G)$.

[18] This rationing rule is a technical assumption which is commonly made in Betrand games with asymmetric costs to guarantee the existence of equilibria. Intuitively one can imagine the entrant undercutting the bid of the incumbent by $\varepsilon$, and making the value of $\varepsilon$ as small as one wants.

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:

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

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

### 3.2. Financial property rights, no secondary market

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 derive the investment and bidding equilibrium assuming that the incumbent owns the financial transmission rights (grandfathering). We assume that there is no secondary market for transmission rights.

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).

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.

**Lemma 3.** *The outcome of the bidding game in the second stage is Betrand-like: If a firm is alone in the market, it sells output at price $C_S$ and makes operational profit $C_S - c$ and $C_S - d$ for the incumbent and the entrant respectively. If both firms are present, the entrant sells at the second highest marginal cost c, and makes an operational profit ($\Delta c$), the incumbent receives a payment ($C_S - c$) from its financial transmission rights.*

**Proof.** See Appendix A □.

**Proposition 2.** *If FTRs are grandfathered to the incumbent, and they cannot be sold in a secondary market, then the incumbent will always invest early, and dynamic efficiency is not achieved.*

**Proof.** We study 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 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 $G < \Delta c$.

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[19]

$$\Delta \Pi_{FTR} = \mu - (1 - \delta) F. \quad (5)$$

The incumbent invests prematurely as

$\Delta \Pi_{FTR} \geq \Delta V_{SP}$. □

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.[20] (b) The term corresponding to the first mover advantage also disappears, because the incumbent is committed anyway to invest in the second period 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 values.

### 3.3. Financial property rights, secondary market

Thus far we assumed that the incumbent is unable to resell the financial transmission rights. 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 3.** *If FTRs are grandfathered to the incumbent and they can be sold in a secondary market, then the equilibrium outcome is dynamically 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 $E_{FTR\to E}^{\text{Wait}} - E_{FTR\to I}^{\text{Wait}} > \Pi_{FTR\to I}^{\text{Wait}}$, 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:

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

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 $E_{FTR\to E}^{\text{Invest}} - E_{FTR\to I}^{\text{Invest}} > \Pi_{FTR\to I}^{\text{Invest}}$. 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 the incumbent obtains profit:

$$\Pi_{FTR,S}^{\text{Invest}} = (\mu - F) + \delta(C_S - c),$$

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

[20] If incumbent enters in period 1 and 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.

**Table 2**
Continuation pay-offs of incumbent and entrant upon obtaining the FTRs in the secondary market. The pay-offs are net of any payments made (or received) in the secondary market and depend on whether the incumbent invested in period 1.

| ***a. I did not invest in period 1*** | **Profit entrant** | **Profit incumbent** |
|---|---|---|
| FTRs to E in secondary market | $E^{\text{Wait}}_{FTR\to E} = \delta(C_s - d - G)$ | $\Pi^{\text{Wait}}_{FTR\to E} = 0$ |
| FTRs to I in secondary market | $E^{\text{Wait}}_{FTR\to I} = \delta \max\{\Delta c - G, 0\}$ | $\Pi^{\text{Wait}}_{FTR\to I} = \delta(C_s - c - F)$ |
| ***b. I invested in period 1*** | **Profit entrant** | **Profit incumbent** |
| FTRs to E in secondary market | $E^{\text{Invest}}_{FTR\to E} = \delta(C_s - d - G)$ | $\Pi^{\text{Invest}}_{FTR\to E} = \mu - F$ |
| FTRs to I in secondary market | $E^{\text{Invest}}_{FTR\to I} = \delta \max\{\Delta c - G, 0\}$ | $\Pi^{\text{Invest}}_{FTR\to I} = (\mu - F) + \delta(C_s - c)$ |

with early investment and

$$\Pi^{\text{Wait}}_{FTR,S} = \delta\left\{(C_S - c - F) + \int_0^{\Delta c} F\, d\Phi(G) + \int_{\Delta c}^{\Delta c + F} (F - \Delta c)\, d\Phi(G)\right\},$$

with delayed investments, where the second and the third term are the additional trading surplus of selling FTRs at price $P$, and subscript $S$ refers to the inclusion of the resale value in the secondary market.

The incumbent will invest in period 1 whenever

$$\Delta\Pi_{FTR,S} = \Pi^{\text{Invest}}_{FTR,S} - \Pi^{\text{Wait}}_{FTR,S} = \Delta V_{SP} \geq 0,$$

which is identical to the social planner's outcome in Eq. (2). □

With the secondary market the incumbent internalizes 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 resale value of the rights.

### *3.4. Physical property rights, secondary market*

This section presents the market equilibrium with a physical property rights approach, an alternative to nodal pricing with financial transmission rights. We assume that the physical property rights are grandfathered to the incumbent before period 1, and can be sold in a secondary market before period 2.[21]

**Proposition 4.** *If PTRs are grandfathered to the incumbent and they can be sold in a secondary market, then the equilibrium outcome is dynamically efficient.*

**Proof.** First, suppose that the incumbent invests in stage 1. 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 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

$$\Pi^{\text{Invest}}_{PTR,S} = \mu - F + \delta\int_0^{\Delta c} (C_S - d - G)\, d\Phi(G) + \delta\int_{\Delta c}^{\overline{G}} (C_S - c)\, d\Phi(G).$$

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

$$\Pi^{\text{Wait}}_{PTR,S} = \delta\int_0^{\Delta c + F} (C_S - d - G)\, d\Phi(G) + \delta\int_{\Delta c + F}^{\overline{G}} (C_S - c - F)\, d\Phi(G).$$

The incumbent invests early if $\Delta\Pi_{PTR,S} = \Pi^{\text{Invest}}_{PTR,S} - \Pi^{\text{Wait}}_{PTR,S} = \Delta V_{SP} \geq 0$, 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 potential resale value of the rights.

## 4. Robustness of results

### *4.1. Alternative models for spot market*

**Table 3**
Continuation profits for incumbent $\Pi$, entrant $E$ and network operator $SO$. Superscripts $M$ and $D$ refer to monopoly and duopoly outcomes.

| Market structure | Incumbent | Entrant | SO |
|---|---|---|---|
| Incumbent alone | $\Pi^M$ | 0 | 0 |
| Entrant alone | 0 | $E^M$ | 0 |
| Both Entrant and Incumbent | $\Pi^D$ | $E^D$ | $SO$ |

Parameters satisfy: $E^M - E^D \geq SO \geq \Pi^M - \Pi^D > \Pi^M - F > 0 > \Pi^D - F$.

One of our main results is that nodal pricing leads to premature investments by the incumbent. Our result depends on assumptions regarding spot market competition: uniform pricing in the spot market, investment capacity equal to the size of the transmission line, full availability of green capacity. In order to study the generality of this result, we introduce reduced-form expressions for expected spot market profits (Table 3) and assume the following inequalities

$$E^M - E^D \geq SO \geq \Pi^M - \Pi^D > \Pi^M - F > 0 > \Pi^D - F. \tag{6}$$

Those inequalities are satisfied in our baseline model[22] and imply among others: Each firm prefers a monopoly situation to a duopoly. There is a private real option value for waiting as the incumbent cannot earn back its fixed costs $F$ based on its duopoly profits. There is also a social real option value, as it might be better to have a monopolistic entrant, than to invest in a duopoly situation: $E^M \geq E^D + \Pi^D + SO - F$.

**Proposition 5.** *Assume that the pay-off structure of spot market competition is given by Table 2, then the monopolist will invest prematurely under nodal pricing.*

**Proof.** See Appendix A. The proof follows the same lines as in Proposition 1. □

The proposition can be used to show that the incumbent overinvests under nodal pricing in more general settings; for instance when production capacity is less than the transmission capacity, production output is stochastic or pay-as-bid auctions. This is shown in the following lemata.

**Lemma 4.** *Let $k$ be the capacity of the incumbent and the entrant with $1 > k > \frac{1}{2}$ and the capacity of the transmission line $K$=1. Let the spot market be organized as a pay-as-bid auction. Then, the incumbent will invest prematurely under nodal pricing.*

**Proof.** See Appendix A. We rely on Fabra et al. (2006) to find the equilibrium in the pay-as-bid auction. □

**Lemma 5.** *Let $k$ be the capacity of the incumbent, and $K$ the capacity of the transmission line. Assume that the entrant's capacity is stochastic: with*

[21] Without secondary market the model would basically turn from a two-period model into a one-period model where all investment decisions are made in period 1 and efficiency is very low. We do not discuss this straightforward case.

[22] In our baseline model we have $SO = \Pi^M$, $\Pi^D$=0 and $E^M = E^D + SO$.

*probability $\rho$ it is $\underline{k}$ and with probability $1-\rho$ it is $\overline{k}$, with $\overline{k} \geq K$ and $\underline{k} \leq K-k$. Then the incumbent will invest prematurely under nodal pricing.*

**Proof**. See Appendix A. □

#### 4.1.1. Downstream market power

We study a market in which a local pocket with market power (North) supplies energy to a large competitive market (South). Obviously, with an additional market failure (market power in the large Southern market), the relative efficiency of scenarios will change. Early investments in the North will limit market power abuse in the South in period 1 which is a positive externality which is not internalized by the incumbent.[23] So the negative first mover effect will be partially offset by a pro-competitive effect.

### 4.2. Alternative settings for transmission rights market

So far we have shown that dynamic efficiency is achieved if the incumbent can make a take-it-or-leave-it offer to the entrant in the secondary market. The incumbent has all bargaining power and therefore internalizes the full real option value. This drives the efficiency result for both for financial and physical transmission rights. We also assumed that the transmission rights were grandfathered to the incumbent, and not allocated in an auction. This subsection progressively relaxes both assumptions.

#### 4.2.1. Bargaining power in secondary market

We assume that the transmission rights are grandfathered to the incumbent and that incumbent and the entrant bargain about the price of the transmission right in the secondary market. As a result of this bargaining, the entrant obtains a fraction $\beta \in [0,1]$ of the gains from trade, and the incumbent a fraction $1-\beta$.[24] Similar derivations as in Section 3 with the additional bargaining parameter $\beta$ are straightforward and not repeated here at length. It can be shown that first stage investment decisions are independent on the type of transmission rights. So the expressions reported below are valid for both types.

If the incumbent looses a fraction $\beta$ of the bargaining surplus to the entrant in the secondary market, it will not internalize a fraction $1-\beta$ of the real option value. The incumbent will invest early in period 1 when

$$\Delta\Pi^{\text{Barg}} = \underbrace{\mu-(1-\delta)F}_{I} - (1-\beta)\underbrace{\delta\left[\int_0^{\Delta c} F\, d\Phi(G) + \int_{\Delta c}^{\Delta c+F} (F+\Delta c-G)\, d\Phi(G)\right]}_{II} > 0.$$

This expression is similar to Eq. (2) but with the option value (II) weighted by the factor $1-\beta$. It is valid both for financial and physical transmissions rights. If $\beta=0$, then the incumbent fully internalizes the externality, and we obtain the first best outcome. The introduction of transmission rights improves upon the situation with nodal pricing without financial transmission rights. If $\beta=1$, then the incumbent has no interest in reselling the transmission rights to the entrant, as the entrant has all the bargaining power, and the outcome converges to the situation of grandfathered FTRs without a secondary market. The incumbent will always invest early. Hence, the introduction of transmission rights reduces overall welfare. We now look at intermediate values of $0<\beta<1$. It can be shown that for $\beta>\hat{\beta}$ with

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

the introduction of financial transmission rights is welfare reducing.[25] Transmission rights will increase welfare 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 ($\Phi(G)$ has large mass on interval $[\Delta c, \Delta c+F]$) so that the first mover effect is large.

#### 4.2.2. Auctioning instead of grandfathering transmission rights

Instead of grandfathering rights to the incumbent we now assume that rights are auctioned. Both the incumbent and the entrant bid for obtaining transmission rights before period 1. The right is then allocated to the highest bidder. If they submit identical bids, the right is allocated randomly. The owner of the transmission right can resell the right in the secondary market and surplus is shared according to a bargaining parameter $\beta$. The following proposition shows that we again obtain dynamic efficiency:

**Proposition 6.** *Let the incumbent and the entrant bid for transmission rights in an auction before period 1, and let them bargain about the rights in a secondary market, then the market equilibrium is dynamically efficient. This is true independent of the level of bargaining power in the secondary market and whether financial or physical transmission rights are used.*

**Proof.** See Appendix A □

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 socially optimal outcome.

## 5. Conclusions

We study dynamic efficiency of access regulation of a bottleneck transmission line in electricity markets. The current practice of organizing short-term markets for those bottlenecks (under nodal pricing in the US or counter-trading in Europe), leads to premature investments by brown incumbent generators. They exploit their first-mover advantage and do not internalize the full social real option value of waiting.

Long-term transmission rights restore dynamic efficiency. By reselling the rights the incumbent internalizes the effects of its investment decisions on the entrant and the network operator. The incumbent will take into account that by investing early, the expected resale value of the transmission rights decreases. Without a secondary market, the situation with long-term rights may actually be *worse* than with nodal pricing.

Regulators can choose between financial and physical transmission rights. We show that dynamic efficiency is achieved with both types of rights. However, as financial rights do not raise concerns regarding short-term strategic withholding of transmission capacity (Joskow and Tirole, 2000), they are the preferred option.

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

[24] Surplus sharing implies bargaining between the two generators over the price of the rights.

[25] The denominator is the investment externality with nodal pricing, the nominator is the social real option value.

Note that long-term property rights have additional benefits which were not explicitly considered in this paper: They allow for explicit coordination of investment decisions which is not possible with nodal pricing alone. They also hedge risks, and can be instrumental in the regulation of new investments in transmission capacity. We therefore encourage regulators to introduce long-term transmission rights, not to grandfather them but auction them instead, and to create liquid secondary markets.


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## Appendix A. Proofs

**Proof of Lemma 3.**

We consider three cases:

1. 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 $(b_E \le b_I)$ 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.
2. If the incumbent is alone in the market, it will always obtain an operational and financial profit equal to $C_S - c$. 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 $b_I$.
3. This is straightforward. The entrant will set a price equal to $b_E = C_S - \varepsilon$ and make a per unit operational profit of $C_s - d$. □

**Proof of Proposition 5.**

**Part 1: Incumbent's incentives.** Investing early and waiting give the following expected pay-offs for the incumbent:

$$V_I^{\text{Invest}} = \mu - F + \delta\Pi^M - \delta\Phi\left(G^0\right)\left(\Pi^M - \Pi^D\right),$$
$$V_I^{\text{Wait}} = \delta\left(1 - \Phi(G^*)\right)\left(\Pi^M - F\right).$$

with $G^0 = E^D$ and $G^* = E^M - \Pi^M + F$. Note that by investing early the incumbent is able to deter entry, that is $G^0 < G^*$ under our assumptions. The incumbent will invest early whenever

$$\Delta V_I = \mu - (1-\delta)F + \delta\Phi(G^*)\left(\Pi^M - F\right) - \delta\Phi\left(G^0\right)\left(\Pi^M - \Pi^D\right) > 0.$$

**Part 2: Social Planner.** Investing early and waiting gives the following expected social surplus:

$$V_{SP}^{\text{Invest}} = \mu - F + \delta\Pi^M - \delta\Phi\left(\hat{G}\right)\left(\Pi^M - \Pi^D - E^D - SO\right) - \delta\int_0^{\hat{G}} G d\Phi(G)$$
$$V_{SP}^{\text{Wait}} = \delta\left(\Pi^M - F\right) + \delta\Phi(G^*)\left(E^M - \Pi^M + F\right) - \delta\int_0^{G^*} G d\Phi(G)$$

with $\hat{G} = \Pi^D + E^D + SO - \Pi^M$, and $G^*$ defined above. Note that the social planner invests less often in the entrant, whenever the incumbent invests early, that is $\hat{G} < G^*$ under our assumptions. The Social Planner invests early when

$$\Delta V_{SP} = \mu - (1-\delta)F - \delta\Phi\left(\hat{G}\right)\left(\Pi^M - \Pi^D - E^D - SO\right)$$
$$-\delta\Phi(G^*)\left(E^M - \Pi^M + F\right) + \delta\int_{\hat{G}}^{G^*} G d\Phi(G) > 0.$$

**Part 3: Comparison:** The incumbent invests too early if $\Delta V_I - \Delta V_{SP} > 0$, or

$$\Phi\left(G^0\right)\left(E^M - E^D - SO\right) + \left(\Phi\left(\hat{G}\right) - \Phi\left(G^0\right)\right)\left(\Pi^M + E^M - \Pi^D - E^D - SO\right)$$
$$+\int_{\hat{G}}^{G^*}\left(E^M - G\right)d\Phi(G) > 0.$$

It can easily be checked that given the inequalities in 6 the first two terms are (weakly) positive and the third term is strictly positive. So the incumbent overinvests. □

**Proof of Proposition 6.**

We derive the proof for financial transmission rights. For physical transmission rights the proof is analogous.

The continuation pay-offs of incumbent and entrant at the start of stage 1 will depend on whether the property rights are obtained by the entrant or the incumbent in the auction. We will use subscripts to indicate those sub-games. Hence, $\Pi_{FTR \Rightarrow I}$ will denote the expected continuation profit of the incumbent ($\Pi$) if the financial transmission rights are obtained by the incumbent in the auction ($FTR \Rightarrow I$). We will use a double arrow to indicate the outcome of the primary auction, while we used the single arrow for the allocation in the secondary market in Table 2. The continuation pay-offs after period 1 will depend additionally on the investment decisions of the incumbent. Those are indicated, as before, with a superscript. Hence $E_{FTR \Rightarrow E}^{\text{Wait}}$, represents the expected continuation profit of the entrant ($E$) if the financial transmission rights are obtained by the entrant ($FTR \Rightarrow E$), and the incumbent did not invest in period 1 (Wait).

The incumbent will outbid the entrant in the primary auction for the FTRs when his valuation for obtaining the rights, $\Pi_{FTR \Rightarrow I} - \Pi_{FTR \Rightarrow E}$, is larger than the entrant's valuation $E_{FTR \Rightarrow E} - E_{FTR \Rightarrow I}$, where $\Pi$ 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, $\Pi_{FTR \Rightarrow I} + E_{FTR \Rightarrow I} > \Pi_{FTR \Rightarrow E} + E_{FTR \Rightarrow E}$. Note that as the network operator does not obtain any congestion rents once the transmission 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:

$$\Pi + E = \begin{cases} (\mu - F) + \delta\left(C_S - c + \int_0^{\Delta c} (\Delta c - G) d\Phi(G)\right) & \text{if } I \text{ invests}, \\ \delta\left[\int_0^{\Delta c + F} (C_S - d - G) d\Phi(G) + \int_{\Delta c + F}^{\overline{G}} (C_S - c - F) d\Phi(G)\right] & \text{if } I \text{ waits}. \end{cases} \tag{7}$$

The incumbent and the entrant will obtain each a share of this joint surplus. The size of their share depends on the bargaining factor $\beta$ 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 $\Delta\Pi = \Pi^{\text{Invest}} - \Pi^{\text{Wait}}$ 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:

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

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

1. $\Delta\Pi_{FTR \Rightarrow I} > \Delta V_{SP} > \Delta\Pi_{FTR \Rightarrow E} > 0$. 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. $\Delta\Pi_{FTR \Rightarrow I} > \Delta V_{SP} > 0 > \Delta\Pi_{FTR \Rightarrow E}$. 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. $\Delta\Pi_{FTR \Rightarrow I} > 0 > \Delta V_{SP} > \Delta\Pi_{FTR \Rightarrow E}$. 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. $0 > \Delta\Pi_{FTR \Rightarrow I} > \Delta V_{SP} > \Delta\Pi_{FTR \Rightarrow E}$. 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.

**Proof of Lemma 4.**

In the duopoly sub-game there is no pure strategy equilibrium in the Bertrand game, but there exists a unique mixed strategy equilibrium (Fabra et al., 2006) in which the firms bid over a common support $[c, C_S]$. We can write the following reduced form expressions (in the case of Bertrand competition profits are derived in p. 40–41 of Fabra et al., 2006):

$$\Pi^M = k(C_S - c), \quad \Pi^D = (1-k)(C_S - c),$$
$$E^M = \Pi^M + k\Delta c, \quad E^D = \Pi^D + k\Delta c,$$
$$SO = (2k-1)(C_S - c),$$

which satisfy the inequalities in Eq. (6). □

**Proof of Lemma 5.**

The reduced form spot market profits are given by

$$\Pi^M = k(C_S - c), \qquad \Pi^D = \rho k(C_S - c),$$
$$E^M = (\rho k + K(1-\rho))(C_S - d), \quad E^D = \rho k(C_S - d) + (1-\rho)K\Delta c,$$
$$SO = (1-\rho)K(C_S - c),$$

which satisfy the inequalities in Eq. (6). □

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