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Do generation firms in restructured electricity markets have incentives to support social-welfare-improving transmission investments?☆

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ABSTRACT

This paper examines the incentives that generation firms have in restructured electricity markets for supporting long-term transmission investments. In particular, we study whether generation firms, which arguably play a dominant role in the restructured electricity markets, have the incentives to fund or support incremental social-welfare-improving transmission investments. We examine this question in a two-node network and explore how such incentives are affected by the ownership of financial transmission rights (FTRs) by generation firms. In the analyzed two-node network, we show both (i) that the net exporter generation firm has the correct incentives to increase the transmission capacity incrementally up to a certain level and (ii) that, although a policy that allocates FTRs to the net exporter generation firm can be desirable from a social point of view, such a policy would dilute the net-importer-generation-firm's incentives to support transmission expansion. Moreover, if all FTRs were allocated or auctioned off to the net exporter generation firm, then it is possible to increase both consumer surplus and social welfare while keeping the net exporter generation firm revenue neutral.

1. Introduction

Although security constrained dispatch is intended to ensure reliability of the power system, there is growing evidence that the U.S. transmission system is under stress (Abraham, 2002). In fact, the National Transmission Grid Study of the U.S. Department of Energy (Abraham, 2002) declares: “Growth in electricity demand and new generation capacity, lack of investment in new transmission facilities, and the incomplete transition to fully efficient and competitive wholesale markets have allowed transmission bottlenecks to emerge. These bottlenecks increase electricity costs to consumers and increase the risks of blackouts… The increased use of the system has led to transmission congestion and less operating flexibility to respond to system problems or component failures. This lack of flexibility has increased the risk of blackouts.” From an economic perspective, increased congestion reduces the ability to import power from remote cheap generators, thus raising the cost of energy. It also impedes trade and competition, which in turn makes consumers more vulnerable to the exercise of market power.

The so-called Standard Market Design (FERC, 2002), which prevails (or is in the process of being implemented) in the restructured electricity markets in the US, relies on locational marginal prices for energy to price and manage congestion and to signal the need for economically driven transmission investments.[1] Studies addressing the insufficiency of incentives for investment in the U.S. electricity transmission system are sparse. Moreover, none of the incentive structures proposed in the literature have been broadly adopted.

Bushnell and Stoft (1996) apply the definition of financial transmission rights (rights that entitle holders to receive financial benefits derived from the use of the capacity) in the context of nodal pricing systems. They use a transmission rights allocation rule based on the concept of feasible dispatch, originally proposed by Hogan (1991), and prove that such a rule can reduce or, under ideal circumstances, eliminate the incentives for a detrimental grid expansion while rewarding efficient investments.

The paper by Bushnell and Stoft (1996) is based on the idea that transmission investors are granted financial rights (which are tradable

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[1] While locational marginal prices provide the right incentives for generation firms to operate efficiently, investments in transmission systems are generally driven by either reliability motives or by the search for a satisfactory rate of return (merchant investment). Many transmission investments in the US are driven by reliability considerations while the economic analysis serves for impact assessment and cost allocation (Abraham, 2002).

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among market participants) as a reward for the transmission capacity added to the network.[2] This scheme, in contrast with the actual rate-of-return-regulation regime, could provide, in principal, the correct incentive for new entrants to invest in new transmission capacity. The main idea in (Bushnell and Stoft, 1996) is that a transmission investor is allowed to select any set of transmission rights which, when combined with the existing set, corresponds to a dispatch that is feasible under the constraints of the newly modified grid. An investor who creates an intentionally congested line, which effectively reduces the feasible set of dispatches, would, therefore, be required to accept a set of transmission rights and obligations that exactly cancel the flows that are no longer feasible in the resulting, lower capacity network. The concept of feasibility, thereby, provides some check on the incentive to create congestion.

Bushnell and Stoft (1996) show that, "under certain conditions", the mentioned simultaneous feasibility test can effectively deter detrimental investments. However, these conditions are very stringent. They assume that transmission investments are characterized by no-increasing returns to scale, there are no sunk costs, nodal prices reflect consumers' willingness to pay for electricity and reliability, all network externalities are internalized in nodal prices, transmission network constraints and associated point-to-point capacity are non-stochastic, there is no market power, markets are always cleared by prices, and the system operator has no discretion to affect the effective transmission capacity and nodal prices over time.

Joskow and Tirole (2003) reexamine the model by Bushnell and Stoft (1996) after introducing assumptions that more accurately reflect the physical and economic attributes of real transmission networks. They show that a variety of potentially significant performance problems then arise. In particular, they claim that the definition of transmission rights by Bushnell and Stoft (1996) does not adequately account for the stochastic and dynamic physical attributes of transmission networks. Thus, they argue that property rights that are "contingent" on exogenous variations in transmission capacity and reflect the diversification attributes of new investments would be required. Unfortunately, defining and allocating these contingent rights is also likely to be inconsistent with the development of liquid competitive markets for these rights or derivatives on them.

In addition, Joskow and Tirole (2003) argue that the difficulty of "correctly" assigning financial transmission rights (FTRs) is another deterrent to invest in the transmission system. In (Bushnell and Stoft, 1996), the allocation of FTRs is made by an independent system operator (ISO) who looks for feasibility of the network using a sequence of simulations of the system. However, these types of assignments may be subjective, especially in the case of allocating incremental network investments (investments that involve upgrades of existing facilities). In this sense, our paper gives some insights about the possibility of using the allocation of FTRs to align the incentives for transmission expansion of the society and of the net exporter generation firms.

The difficulty of correctly assigning FTRs is also addressed in Barmack et al. (2003). Differently from Joskow and Tirole (2003), they mention two other important reasons for the inefficiency of FTRs with respect to incentives for transmission investment: (i) a transmission investment that eliminates congestion results in FTRs that are worthless, and (ii) it may be difficult for transmission owners (TOs) to capture other benefit streams resulting from transmission investment.

Joskow and Tirole (2000) analyze how the allocation of transmission rights associated with the use of power networks affects the operational behavior of generation firms and consumers with market power. Their analysis, as well as the analysis in (Joskow and Tirole, 2003), focuses on an always-congested two-node network where there is a cheap generation monopolist in an exporting region that has no local demand and an expensive generation monopolist in an importing region that contains the entire-system demand. They conclude that if the generation firm in the importing region has market power, its holding of financial transmission rights enhances that market power since the FTRs give it an extra incentive to curtail its output to make the rights more valuable. In Section 3.2 of this paper, we reach the same conclusion and, in addition, we analyze the consequences of this finding on the incentives that generation firms have to support social-welfare-improving transmission expansions.

Joskow and Tirole (2000) also conclude that, considering there is no local demand at the node where the net exporter generation firm is located, social welfare is likely reduced by the ownership of FTRs by the net importer generation firm because this would incentivize the net importer firm to increase prices. In Section 3.2 of this paper, we show that allocating FTRs to a net exporter generation firm who both has local market power and faces local demand with some elasticity, may compensate this social-welfare-reducing effect due to the incentive of the net exporter firm to reduce its nodal price to make transmission rights more valuable.

Several related studies try to improve the incentive structures for transmission investment by dealing with the generator's motivation to exercise market power. In Cardell et al. (1997), Joskow and Tirole (2000), Oren (1997) and Stoft (1999), the authors study the implications of the exercise of market power in congested two- and/or three-node networks where the entire system demand is concentrated in only one node. The main idea behind these papers is that if an expensive generator with local market power is required to produce power as a result of network congestion, then the generation firm owning this generator may have a disincentive to relieve congestion. Borenstein et al. (2000) present an analysis of the relationship between transmission capacity and generation competition in the context of a two-node network in which there is local demand at each node. The authors argue that relatively small transmission investment may yield large payoffs in terms of increased competition. However, they only consider the case in which generation firms cannot hold transmission rights. In Section 3.2 of this article, we extend this analysis to allow both local demand at each node of the network and the possibility that generation firms hold financial transmission rights.

The California Independent System Operator (CAISO) has recently developed a "Transmission Economic Assessment Methodology" (TEAM) for assessing transmission expansion projects, which is based on the *gains from trade* principle (Sheffrin, 2005; CAISO, 2004). Although TEAM considers alternative generation-expansion scenarios with and without transmission upgrades, as far as we know, this generation-expansion analysis does not take into account the potential strategic response to transmission investment from generation firms who may alter their investment plans in new generation capacity. This rationale underlines common wisdom that prevailed in a regulated environment justifying the construction of transmission between cheap and expensive generation nodes on the grounds of reducing energy cost to consumers. However, as shown by Sauma and Oren (2006), such rationale may no longer hold in a market-based environment where market power is present.

On the other hand, FERC has recently proposed transmission pricing reforms designed to promote needed investment in energy infrastructure (FERC, 2005). Basically, FERC proposes an increase in the rate of return on equity, especially for stand-alone transmission companies (Transcos), in order to both attract new investment in transmission facilities and encourage formation of Transcos. This FERC proposal is based on the idea that incentives may be more effective in fostering new transmission investment for Transcos than for traditional public utilities that are dependent upon retail regulators for some portion of their transmission cost recovery.

[2] The concept of a decentralized allocation of financial transmission rights was originally developed by Hogan (1991, 1992), under the name of "contract network regime".

In this paper, we focus on the incentives that generation firms at generation pockets have to support incremental social-welfare-improving transmission expansions and how these incentives are affected by the ownership of financial transmission rights (FTRs). We are interested in analyzing the effect of local market power on such incentives when considering two cases: that generation firms can hold FTRs and that generation firms cannot hold FTRs. For simplicity, we will assume through this article that transmission line capacities are static and deterministic.

The rest of the paper is organized as follows. Section 2 studies the distributional impacts of transmission investments. In Section 3, we explore how FTRs allocation may be used to align the incentives for transmission expansion of the society and of the net exporter generation firms, in the context of a two-node network. We illustrate the theoretical results obtained in Section 3 through a numerical example presented in Section 4. Section 5 concludes the paper.

2. Distributional impacts of transmission investments

Before analyzing the transmission investment incentives of generation firms, it is worth to emphasize the well-known fact that transmission expansions generally have distributional impacts, which could potentially create conflicts of interests among the affected parties. The key issue is that, while society as a whole may benefit from incremental mitigation of congestion, some parties may be adversely affected.

In general, transmission investment effects rent transfers from load pocket generators and generation pocket consumers to load pocket consumers and generation pocket generators. However, load pocket consumers and generation pocket generators cannot simply decide to build a line linking them. Their decision will be subject to scrutiny by not only an ISO, but also state and federal energy and environmental regulators. In this type of environment, the "losers" from transmission investment could be expected to expend up to the amount of rents that they stand to lose to block the transmission investment. This rent dissipation is wasteful. Moreover, it may block socially beneficial projects from being built. Nevertheless, it is important to mention that the usual coordination problem faced by the beneficiaries of a transmission expansion also applies to the losers from the expansion. The following examples illustrate the distributional impacts of transmission investments and the potential incentives that some market participants could have to exercise political power in order to block a social-welfare-improving transmission expansion project.

Consider a network composed of two cities satisfying their electricity demand with local generation firms. For simplicity, assume there exists only one (monopolist) generation firm in each city, which have unlimited generation capacity. We assume that the marginal cost of supply at city 1 is lower than that at city 2. In particular, suppose the marginal costs of generation are constant[3] and equal to zero at city 1 and $20/MWh at city 2. Assume the inverse demand functions are linear, given by $P_1(q) = 100 - 0.1 \cdot q$ at city 1 and by $P_2(q) = 120 - 0.2 \cdot q$ at city 2, in $/MWh.

Under the monopolistic (self-sufficient-cities) scenario, the city 1 firm optimally produces $q_1^{(M)} = 500$ MWh (on an hourly basis) and charges a price $P_1^{(M)} = \$50$/MWh while the city 2 firm optimally produces $q_2^{(M)} = 250$ MWh and charges a price $P_2^{(M)} = \$70$/MWh. With these market-clearing quantities and prices, the firms' profits are $\Pi_1^{(M)} = \$25{,}000$/h and $\Pi_2^{(M)} = \$12{,}500$/h, respectively. The consumer surpluses are $CS_1^{(M)} = \$12{,}500$/h for city 1 consumers and $CS_2^{(M)} = \$6250$/h for city 2 consumers.[4]

Now, consider the scenario in which there is unlimited transmission capacity between the two cities. This situation corresponds to a duopoly facing an aggregated demand given by (in $/MWh):

$$P(Q) = \begin{cases} 120 - 0.2 \cdot Q & , \text{ if } Q < 100 \\ 106.66 - 0.066 \cdot Q & , \text{ if } Q \geq 100 \end{cases}, \text{ where } Q = q_1 + q_2.$$

We assume that generation firms behave as Cournot oligopolists in this case. Under this scenario, the firm at city 1 optimally produces $q_1^{(D)} = 633$ MWh (on an hourly basis) while the firm at city 2 optimally produces $q_2^{(D)} = 333$ MWh. The price charged by both firms is equal to $P^{(D)} = \$42.2$/MWh. With these new market-clearing quantities and price, the firms' profits are $\Pi_1^{(D)} = \$26{,}741$/h and $\Pi_2^{(D)} = \$7407$/h, respectively.[5] Furthermore, the consumer surpluses are $CS_1^{(D)} = \$16{,}691$/h for the city 1 consumers and $CS_2^{(D)} = \$15{,}124$/h for the city 2 consumers.

In this example, by linking both cities with a high-capacity transmission line, we replace some expensive power produced at city 2 by cheaper power generated at city 1, which makes city 2 consumers clearly better off. Unfortunately, this is not the only implication of the construction of such a transmission line. The city 2 firm reduces its profit because its retail price decreases as result of the competition between generation firms introduced by the new transmission line.

Indeed, the numerical results reveals that the construction of the transmission line has the following consequences: the city 1-consumers' surplus increases from $12,500/h to $16,691/h, the city 2-consumers' surplus increases from $6250/h to $15,124/h, the city 1-firm's profit increases from $25,000/h to $26,741/h, and the city 2-firm's profit decreases from $12,500/h to $7407/h. From these results, it is clear that the city 2 firm (load pocket generator) will oppose the construction of the line linking both cities because this line will decrease its profit, transferring its rents to the other market participants. Consequently, depending on the relative political power of the city 2 firm, this network-expansion project could be blocked, even though it could be socially beneficial (depending on the transmission investment costs).[6]

The problem of rent transfer may arise even in the absence of market power. To illustrate this fact, assume that city 1 (generation pocket) has 1000 MW of local generation capacity at $10/MWh marginal cost and another 500 MW of generation capacity at $20/MWh marginal cost, with 600 MW of local demand, while city 2 has 800 MW of generation capacity at $30/MWh marginal cost and local demand of 1000 MW. Furthermore, assume that all generation power is offered at marginal cost and that a 300 MW transmission line connects the two cities. Under this scenario, the market clearing prices are $10/MWh in city 1 and $30/MWh in city 2 and 300 MW are exported from city 1 to city 2. A 300 MW increase in transmission capacity would allow replacement of 300 MW of load served at $30/MWh by imports from city 1, of which 100 MW can be produced at $10/MWh and another 200 MW can be produced at $20/MWh. The social benefit from such an expansion is, therefore, $4000/h. Assuming that the amortized upgrade costs is below $4000/h, the upgrade is socially beneficial. The market consequences of such an upgrade are that the market clearing price at city 1 increases from $10/MWh to $20/MWh while the market clearing price at city 2 stays $30/MWh as before,

[3] The assumption that marginal costs of supply are constant is not critical, but it simplifies calculations.

[4] Under monopoly, a firm optimally chooses a quantity such that the marginal cost of supply equals its marginal revenue. If the marginal cost of production is constant and equal to c and the demand is linear, given by $P(q) = a - b \cdot q$, where $a > c$, then the monopolist will optimally produce $q^{(M)} = (a-c)/(2b)$ and charge a price $P^{(M)} = (a+c)/2$, making a profit of $\Pi^{(M)} = (a-c)^2/(4b)$. Under these assumptions, the consumer surplus is equal to $CS^{(M)} = (a-c)^2/(8b)$.

[5] Under duopoly, the Cournot firms simultaneously choose quantities such that their marginal cost of supply equals their marginal revenue, but assuming the quantity produced by the other firm is fixed. If the marginal costs of production are constant for both firms, given by c_1 and c_2 respectively, and the aggregate inverse demand is linear, given by $P(Q) = A - B \cdot Q$, where $A > c_1$ and $A > c_2$, then firm i will optimally produce $qi^{(D)} = (A - 2c_i + c_j)/(3B)$, with $j \neq i$ and $i \in \{1,2\}$. Under these assumptions, the duopolistic price will be $P^{(D)} = (A + c_1 + c_2)/3$ and firm i will make a profit of $\Pi_i^{(D)} = (A - 2c_i + c_j)2/(9B)$, with $j \neq i$ and $i \in \{1,2\}$.

[6] Note that, in general, building transmission to eliminate all congestion is not necessarily optimal (especially when construction cost is accounted for), but it can be superior to the case of no connectivity. In our example, we do not advocate elimination of congestion, but use these two polar extremes for illustrative purposes.

with 600 MW being exported from city 1 to city 2. Thus, consumers and generators in city 2 are neutral to the expansion, consumer surplus in city 1 will drop by \$6000/h, generator's profits in city 1 will increase by \$10,000/h, and the merchandising surplus of the system operator will remain unchanged (the ISO merchandising surplus on the pre-expansion imports drops \$3000/h, but it picks up \$3000/h for the incremental imports). Clearly, such an expansion is likely to face stiff opposition from consumers in city 1, but it would be strongly favored by the generators at city 1, who would be more than happy to pay for it (as long as the amortized investment cost does not exceed \$10,000/h). In fact, generators at node 1 would favor such an investment even if its amortized cost exceed the \$4000/h benefits, which would make such an investment socially inefficient to the detriment of city 1 consumers.

By contrast to the above example, a small incremental upgrade of 90 MW in the transmission capacity would be socially beneficial increasing social surplus by \$1800/h without affecting the market clearing prices in either city. In such a case, neither the generators nor the consumers on either side will benefit (or be harmed) by the expansion and, thus, the entire gain will go to the ISO in the form of merchandising surplus. In such a case, a merchant transmission owner could be induced to undertake the transmission upgrade in exchange for financial transmission rights (FTRs) that would entitle her to the locational marginal price differences for the incremental capacity, thus allowing the investor to capture the entire social surplus gain due to the expansion.

In the following section, we will further explore how FTR allocation may be used to align the incentives for transmission expansion of the society and of some market participants.

3. Transmission investment incentives of generation firms

In analyzing the transmission investment incentives of generation firms, considering the implications of the exercise of local market power by generators becomes crucial. Here, we study this idea in the context of a radial, two-node network and explore how the investment incentives are affected by the ownership of financial transmission rights (FTRs) by generation firms. The analysis in this section shows that the net exporter generation firm has the correct incentives to increase the transmission capacity incrementally up to certain level. We also show that, although allocating FTRs to the net exporter generation firm can increase its incentives to support a social-welfare-improving transmission expansion, such a policy would dilute the net-importer-generation-firm's incentives to support the capacity expansion. We also show that, if all FTRs were allocated or auctioned off to the net exporter generation firm, then it is possible to increase both consumer surplus and social welfare while keeping the net exporter firm revenue neutral.

As general framework for the analysis presented in this section, we assume that the transmission system uses locational marginal pricing, generation firms behave as Cournot oligopolists, transmission losses are negligible, all transmission rights are financial rights (whose holders are rewarded based on congestion rents), and network investors are rewarded based on a regulated rate of return administered by a non-profit ISO, which manages transmission assets owned by many investors. The main two reasons for this choice are: (i) many of the U.S. transmission systems actually use this type of scheme and (ii) this structure has been proposed by FERC as part of its Standard Market Design (FERC, 2002).

Consider a network composed of two nodes linked by a transmission line of thermal capacity K. The non-depreciated capital and operating costs of the link are assumed to be recovered separately from consumers (for instance, in lump-sum charges net of revenues produced by selling transmission rights) and we do not consider these costs further in our analysis.

For simplicity, we assume that there is only one generation firm at each node, having unlimited generation capacity. We assume that the production cost functions of the two firms, say $C_1(q)$ and $C_2(q)$, are convex and twice differentiable in the firms' outputs (i.e., the firms' marginal costs of generation are continuously non-decreasing in the firms' outputs). We also assume that the inverse demand function at each node of the network, say $P_1(q)$ at node 1 and $P_2(q)$ at node 2, is continuous, concave, and downward sloping. Moreover, we suppose that, if the two markets were completely isolated (i.e., no connected by any transmission line), the generation firms would produce outputs q_1^M and q_2^M such that $P_1(q_1^M)<P_2(q_2^M)$.[7]

Let q_i ($i=1,2$) be the quantity of energy produced by the generation firm located at node i, and let q_t be the net quantity exported from node 1 to node 2. This quantity (q_t) depends on both nodal prices and, thus, depends on both q_1 and q_2. Moreover, q_t must satisfy the transmission capacity constraints (i.e., it must satisfy $-K \le q_t \le K$, where a negative q_t represents a net flow from node 2 to node 1).

Our analysis considers two scenarios: first, a scenario in which generation firms cannot hold transmission rights and second, a scenario in which generation firms can hold FTRs.

3.1. Scenario I: generation firms cannot hold transmission rights

Assume generation firms cannot hold transmission rights (and, thus, their bidding strategy is independent of the congestion rent). Accordingly, in this case, the profit of the generation firm located at node 1 (cheapgen) is $\pi_1(q_1)=q_1\cdot P_1(q_1-q_t)-C_1(q_1)$ and the profit of the generation firm located at node 2 (deargen) is $\pi_2(q_2)=q_2\cdot P_2(q_2+q_t)-C_2(q_2)$. Implicit on these definitions is the assumption that each market participant must trade power with an ISO, at the nodal price of its local node. Thus, the generation firm located at node i will receive a payment equal to the nodal price at node i times the quantity produced and the consumers at node j will pay an amount equal to the nodal price at node j times the quantity consumed. Consequently, the nodal price that each firm faces is determined by local generation plus imports.

When generation firms cannot hold transmission rights, it is relatively simple to analyze the incentives that generation firms with local market power have to support social-welfare-improving transmission investments. We could argue that, by congesting the system,[8] generation firms have the ability to exercise their local market power and deliberately withhold their outputs so that they can increase their profits. However, we must be cautious in the analysis of the equilibrium conditions because nodal prices, $P_1(q_1-q_t)$ and $P_2(q_2+q_t)$ in our example, are discontinuous at the point where the transmission line becomes congested (i.e., at $q_t=\pm K$).

In Borenstein et al. (2000), the authors use a two-node network similar to the one described above. They showed that, as the thermal capacity of the transmission line, K, increases from zero, one of two possible outcomes is obtained:[9]

$$\text{Case 1}: \begin{cases} 0 < K < K' & \text{passive/aggressive (P/A) Nash equilibrium exists} \\ K' < K < K^* & \text{no pure-strategy Nash equilibrium exists} \\ K^* < K & \text{unconstrained Nash}-\text{Cournot equilibrium exists} \end{cases}$$

or

$$\text{Case 2}: \begin{cases} 0 < K < K^* & \text{P/A Nash equilibrium exists} \\ K^* < K < K' & \text{both P/A and unconstrained Cournot Nash equilibria exist} \\ K' < K & \text{unconstrained Nash}-\text{Cournot equilibrium exist} \end{cases}$$

[7] This would be the case if, for example, both generation firms faced equal demand curves (i.e., $P_1(q)=P_2(q)$) and the marginal cost of supply at node 1 were lower than that at node 2 over the relevant range (i.e., $C_1'(q_1^M)<C_2'(q_2^M)$).

[8] In this article, the term "congestion" is used in the electrical engineering sense: a line is congested when the flow of power is equal to the line's thermal capacity, as determined by various engineering standards.

[9] See Theorem 5 in Borenstein et al. (2000).

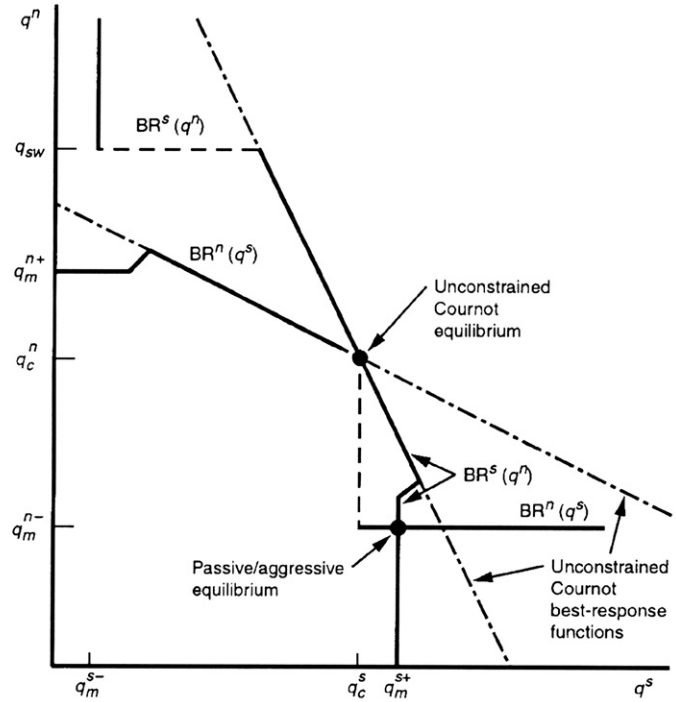

Fig. 1. Best-response functions in the overlapping equilibria case. Reproduced from Fig. 7 in Borenstein et al. (2000).

where K' corresponds to the largest line capacity that can support a P/A Nash equilibrium (i.e., a pure-strategy Nash equilibrium in which the transmission line is congested with net flow from the lower-price — under monopoly — market to the higher-price market) and K^* represents the smallest transmission line capacity that can support an unconstrained[10] Nash–Cournot duopoly equilibrium (i.e., a Nash–Cournot duopoly equilibrium in which K is high enough so that the line is never congested).

One can derive the best-response (in quantity) functions of each firm for each one of the two previous cases. Fig. 1, reproduced from (Borenstein et al., 2000), illustrates the best-response functions in case 2 (i.e., the overlapping equilibria case), where firm s and n are the cheapgen and the deargen, respectively, and where q_m^{n+}, q_m^{n-}, q_m^{s+}, and q_m^{s-} represent the profit-maximizing output (PMO) for firm n when it is congesting the line to s, the PMO for firm n when it is producing its optimal passive output, the PMO for firm s when it is congesting the line to n, and the PMO for firm s when it is producing its optimal passive output, respectively.

When firm n is producing nothing, the best response of firm s is to produce its optimal quantity given that the line will be congested from s to n. As n's output rises, eventually it reaches the point at which it becomes more profitable for s to switch to a much less aggressive output response. Practically any asymmetry (in either costs or demand) will result in a pure-strategy P/A equilibrium for a sufficient small line. As the capacity of the line increases, export from the low-price market (s) increases. This shifts rightward the demand that s faces and, thus, rises the price at s. As exports into n increase with the increase in K, firm n will reduce production, but by less than the increase in imports to n, so the price in n will drop. The higher K makes it less attractive for n to allow the line to be congested into its market. For a line capacity greater than some level, firm n is better off acting more aggressively, which eliminates the P/A equilibrium. Moreover, as K increases, eventually a point must be reached at which a pure-strategy unconstrained Cournot duopoly equilibrium can be supported, as Fig. 1 suggests.

Accordingly, if the transmission line capacity is high enough (i.e., $K > Max\{K', K^*\}$), then an unconstrained Nash–Cournot duopoly equilibrium exists and it corresponds to the unique pure-strategy Nash equilibrium. In this case, there is no congestion at the Nash equilibrium and q_t is far enough from $\pm K$ so that both $P_1(q_1 - q_t)$ and $P_2(q_2 + q_t)$ are continuous and differentiable over the relevant range. Thus, the unconstrained Nash–Cournot duopoly equilibrium (in which each firm maximizes its profit taking the output of the other firm as fixed subject to the fact that nodal prices must be equal at both nodes) is characterized by the following system of equations (first order optimality conditions):

$$P_1(q_1 - q_t) + q_1 \cdot \frac{d(P_1(q_1 - q_t))}{dq_1} = C_1'(q_1), \tag{1}$$

$$P_2(q_2 + q_t) + q_2 \cdot \frac{d(P_2(q_2 + q_t))}{dq_2} = C_2'(q_2), \tag{2}$$

$$P_1(q_1 - q_t) = P_2(q_2 + q_t), \tag{3}$$

$$-K < q_t < K, \tag{4}$$

$$q_1, q_2 \geq 0. \tag{5}$$

These optimality conditions are only valid under the assumption that, at the equilibrium, q_t is far enough from $\pm K$. The only way to guarantee this fact is by ensuring that the transmission line capacity is high enough so that the line is never congested. However, this is not an interesting case to analyze from the point of view of the transmission investment incentives because generation firms have obviously no incentives to support an increment in the capacity of a line that has large excess capacity.

On the other hand, if the transmission line capacity is low enough (i.e., $K < Min\{K', K^*\}$), then generation firms act according to a Nash equilibrium in which the transmission line is congested with net flow from the lower-price (under monopoly) market to the higher-price market (i.e., a P/A Nash equilibrium). In this case, $q_t = K$ (i.e., the line is congested with net flow from node 1 to node 2) and the discontinuity of both $P_1(q_1 - q_t)$ and $P_2(q_2 + q_t)$ at the point where the line is congested

[10] In this paper, the term "unconstrained" refers to the fact that the transmission constraint is not binding.

becomes problematic in the sense that, as q_t approaches to K, $d(P_1(q_1-q_t))/dq_1$ and $d(P_2(q_2+q_t))/dq_2$ are not well defined and, thus, Eqs. (1) and (2) cannot correctly represent the optimality conditions. In this case, as mentioned before, as the capacity of the line increases, eventually a point must be reached at which a pure-strategy unconstrained Cournot duopoly equilibrium can be supported. Moving the line capacity from slightly below this level to slightly above this level may cause a discontinuous jump of the equilibrium from a P/A equilibrium to an unconstrained Cournot equilibrium.

Consider a P/A point of operation, (q_1^c, q_2^c), that maximizes the firms' profits given that the quantity exported from node 1 to node 2 is fixed and equal to the line capacity (i.e., subject to the fact that the line is congested with flow from node 1 to node 2). That is, q_1^c is the profit-maximizing output of the cheapgen when it faces an inverse demand curve given by $P_1(q_1-K)$, which is the cheapgen's native inverse demand shifted rightward by K, and q_2^c is the output of the deargen when it maximizes its profit given the residual inverse demand it faces, $P_2(q_2+K)$, which is the deargen's native inverse demand shifted leftward by K. In this case, the cheapgen effectively acts as a monopolist on the rightward-shifted inverse demand curve and the deargen effectively acts as a monopolist on its residual inverse demand curve. Borenstein et al. (2000) show that, for sufficiently small transmission capacity, the quantities (q_1^c, q_2^c) are the unique pure-strategy Nash equilibrium.[11] Although the proof presented in Borenstein et al. (2000) correctly analyzes the incentives that the generation firms have not to deviate from the equilibrium, the fact that both $P_1(q_1-q_t)$ and $P_2(q_2+q_t)$ are discontinuous at the point where the line is congested and the associated complexities are not explicitly addressed in the proof. In Sauma (2005), an alternative proof is provided showing that (q_1^c, q_2^c) is a pure-strategy Nash equilibrium, that accounts for all possible discontinuities. We omit the detailed proof due to space limitation and summarize in Table 1 below the basic rationale.

Now, we analyze the incentives/disincentives that the generation firms have to support an increase in the capacity of the transmission line while the Nash equilibrium characterized by (q_1^c, q_2^c) prevails.[12] Here, we will assume that such an increase in the transmission capacity is desired because it would increase both the total consumer surplus and the social welfare, as it is more likely to happen in a congested radial network according to the *gains from trade* economic principle (Sheffrin, 2005).

Suppose the thermal capacity of the transmission line is increased by a small positive amount, ΔK, such that the P/A Nash equilibrium is still supported. Then, the cheapgen will act as a monopolist on the $(K+\Delta K)$-rightward-shifted inverse demand curve and, consequently, it will reoptimize its profit by increasing its output so that q_t is augmented by ΔK (i.e., congest the line again). Accordingly, the cheapgen's new optimal output, $q_1^{c(K+\Delta K)}$, will be larger than q_1^c and the new optimal price at node 1, $P_1(q_1^{c(K+\Delta K)}-(K+\Delta K))$, will be greater or equal to that before the expansion (because the consumption at node 1 must either decrease or remain equal at the new optimum). Lemma 1 formally proves these facts.[13]

[11] See Theorem 4 in Borenstein et al. (2000).

[12] Hereafter in this section, we assume that (q_1^c, q_2^c) is an "interior" passive/aggressive Nash equilibrium, where by "interior" we will understand that it is a passive/aggressive Nash equilibrium that prevails when the line capacity is increased by a small amount.

[13] An intuitive way to understand the results proved on Lemma 1 is the following. When the thermal capacity of the transmission line increases by ΔK, the cheapgen could increase its output in ΔK and keep the same retail price at node 1 (making node 1 consumers indifferent and node 2 consumers better off), obtaining an extra profit equal to $\Delta K\cdot P_1(q_1^c-K)$. However, the fact that the cheapgen now faces a higher demand motivates it to exercise its local market power, reducing its output from the theoretical $q_1^c+\Delta K$ (while, of course, still resulting in an output greater than q_1^c) in order to increase the price at node 1 and, thus, increase its profit. That is, the cheapgen will now act as a monopolist on the $(K+\Delta K)$-rightward-shifted inverse demand curve and reoptimize its profit by increasing its output in such a way so that the line is congested and the profit gained due to the nodal price increase, $q_1^{c(K+\Delta K)}\cdot(P_1(q_1^{c(K+\Delta K)}-(K+\Delta K))-P_1(q_1^c-K))$, is larger than the profit "lost" due to the fact that the output is increased by less than ΔK, $(q_1^c+\Delta K-q_1^{c(K+\Delta K)})\cdot P_1(q_1^c-K)$. Fig. 2 illustrates these facts.

Table 1
Rationale of proof that (q_1^c, q_2^c) is a Nash equilibrium.

Firm	Deviation	Possible scenarios	Consequence
Cheapgen	Decrease output $q_1^c\to q_1^c-\varepsilon$ $(\varepsilon>0)$	(i) q_t unchanged and $(q_1^c-q_t)$ decreases by ε	Line still congested, $P_1(q_1^c-q_t)$ increases, $(q_1^c-q_t)$ decreases $\Rightarrow \pi_1$ decreases.
		(ii) q_t decreases by ε and $(q_1^c-q_t)$ unchanged	Line decongested $\Rightarrow$ it is optimal to congest the line again.
		(iii) both q_t and $(q_1^c-q_t)$ decrease by less than ε.	Line decongested, π_1 decreases $\Rightarrow$ it is optimal to congest the line again.
Cheapgen	Increase output $q_1^c\to q_1^c+\varepsilon$ $(\varepsilon>0)$	(i) q_t unchanged and $(q_1^c-q_t)$ increases	Line still congested, $P_1(q_1^c-q_t)$ decreases, $(q_1^c-q_t)$ increases $\Rightarrow \pi_1$ decreases.
		(ii) q_t decreases and $(q_1^c-q_t)$ increases	Line decongested, $P_1(q_1^c-q_t)$ decreases $\Rightarrow$ it is optimal to congest the line again.
Deargen	Increase output $q_2^c\to q_2^c+\varepsilon$ $(\varepsilon>0)$	(i) q_t unchanged and $(q_2^c+q_t)$ increases by ε	Line still congested, $P_2(q_2^c+q_t)$ decreases, $(q_2^c+q_t)$ increases $\Rightarrow \pi_2$ decreases.
		(ii) q_t decreases by ε and $(q_2^c+q_t)$ unchanged	Line decongested $\Rightarrow$ it is optimal to allow a congested line again.
		(iii) q_t decreases by less than ε and $(q_2^c+q_t)$ increases	Line decongested, π_2 decreases $\Rightarrow$ it is optimal to allow a congested line again.
Deargen	Decrease output $q_2^c\to q_2^c-\varepsilon$ $(\varepsilon>0)$	(i) q_t unchanged and $(q_2^c+q_t)$ decreases	Line still congested, $P_2(q_2^c+q_t)$ increases, $(q_2^c+q_t)$ decreases $\Rightarrow \pi_2$ decreases.
		(ii) both q_t and $(q_2^c+q_t)$ decrease	Line decongested, $P_2(q_2^c+q_t)$ increases $\Rightarrow$ it is optimal to allow a congested line again.

Lemma 1. *In the two-node network described in this section, assume that a passive/aggressive Nash equilibrium is achieved and that a passive/aggressive Nash equilibrium is still supported when making an incremental transmission investment. Then, the change in the equilibrium cheapgen's output due to an incremental transmission expansion is positive, but smaller than the change in the transmission capacity.*

Proof. Assume that the Nash equilibrium characterized by (q_1^c, q_2^c), with $q_1^c>0$ and $q_2^c>0$, is achieved and that a P/A Nash equilibrium is still supported when making an incremental transmission investment. Since generation firms cannot hold transmission rights, the profit of the cheapgen at the equilibrium is: $\pi_1^*(q_1^c,K)=q_1^c\cdot P_1(q_1^c-K)-C_1(q_1^c)$. Hence, the first order optimality condition is: $d\pi_1^*/dq_1^c=0$, or equivalently: $P_1(q_1^c-K)+q_1^c\cdot P_1'(q_1^c-K)-C_1'(q_1^c)=0$. Then, $d^2(\pi_1^*(q_1^c,K))/dK\,dq_1^c=0$, or:

$$P_1'(q_1^c{}^*-K)\cdot\left(\frac{dq_1^c{}^*}{dK}-1\right)+\frac{dq_1^c{}^*}{dK}\cdot P_1'(q_1^c{}^*-K)+q_1^c{}^*\cdot P_1''(q_1^c{}^*-K)\cdot\left(\frac{dq_1^c{}^*}{dK}-1\right)-C_1''(q_1^c{}^*)\cdot\frac{dq_1^c{}^*}{dK}=0 \quad (6)$$

or equivalently:

$$\frac{dq_1^c{}^*}{dK}=\frac{P_1'(q_1^c{}^*-K)+q_1^c{}^*\cdot P_1''(q_1^c{}^*-K)}{2\cdot P_1'(q_1^c{}^*-K)+q_1^c{}^*\cdot P_1''(q_1^c{}^*-K)-C_1''(q_1^c{}^*)}. \quad (7)$$

Since $q_1^c{}^*>0$, costs functions are convex, and the inverse demand functions are continuous, concave, and downward sloping, every term of both the numerator and the denominator of the right-hand side of Eq. (7) is negative. Thus, $dq_1^c{}^*/dK$ is positive. Furthermore, since $|2\cdot P_1'(q_1^c{}^*-K)+$

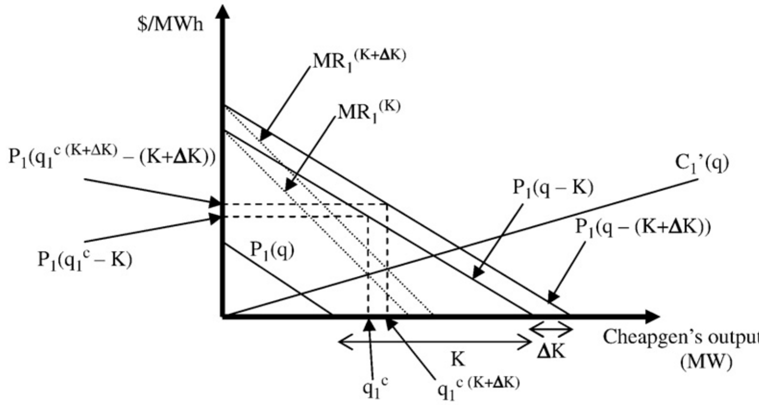

Fig. 2. Transmission investment incentives of the cheapgen in the two-node network.

$q_1^c * \cdot P_1''\ (q_1^c * - K) - C_1''\ (q_1^c *)| > |P_1'\ (q_1^c * - K) + q_1^c * \cdot P_1''\ (q_1^c * - K)|$, we have that $\mathrm{d}q_1^c * / \mathrm{d}K < 1$, which implies that the change in the equilibrium cheapgen's output due to an incremental transmission expansion is smaller than the change in the transmission capacity. □

Following Lemma 1, it becomes evident that the cheapgen will have positive incentives to support this transmission expansion because it increases the cheapgen's profit. Fig. 2 illustrates this situation (where $MR_1^{(K)}$ represents the marginal revenue when the cheapgen faces the K-rightward-shifted inverse demand curve and $MR_1^{(K+\Delta K)}$ corresponds to the marginal revenue when the cheapgen faces the $(K+\Delta K)$-rightward-shifted inverse demand curve). Proposition 1 summarizes this intuitive result.

Proposition 1. *Assume that generation firms cannot hold transmission rights. In the two-node network described in this section,*[14] *the net exporter generation firm (i.e., the cheapgen) has positive incentives to support an increase in the transmission capacity up to any level so that a passive/aggressive Nash equilibrium is still supported.*

Proof. Assume that the Nash equilibrium characterized by (q_1^c, q_2^c), with $q_1^c > 0$ and $q_2^c > 0$, is achieved and that a P/A Nash equilibrium is still supported when making an incremental transmission investment. Since generation firms cannot hold transmission rights, the profit of the cheapgen at the equilibrium is: $\pi_1^*\ (q_1^c, K) = q_1^c \cdot P_1(q_1^c - K) - C_1(q_1^c)$.

By using the envelope theorem, we obtain:

$$\frac{\mathrm{d}(\pi_1^*(q_1^c, K))}{\mathrm{d}\,K} = q_1^c \cdot P_1'(q_1^c - K) \cdot (-1) = -q_1^c \cdot P_1'(q_1^c - K). \tag{8}$$

Since $q_1^c > 0$ and the inverse demand functions are continuous and downward sloping (i.e., $P_1'(q_1^c - K) < 0$), we have from Eq. (8) that: $\mathrm{d}(\pi_1^*\ (q_1^c,\ K))/\mathrm{d}\ K > 0$. This is, the equilibrium cheapgen's profit increases as the transmission capacity increases, as long as a P/A Nash equilibrium is still supported. Consequently, the cheapgen has positive incentives to support an increase in the transmission capacity up to any level so that a P/A Nash equilibrium is still supported. □

On the other hand, when the line capacity is increased by the small positive amount, ΔK, the deargen's best response is to produce its optimal "passive" output. That is, the deargen will act as a monopolist on its residual, $(K+\Delta K)$-leftward-shifted, inverse demand curve and reoptimize its profit by decreasing its output. The new optimal output, $q_2^{c(K+\Delta K)}$, will be smaller than q_2^c and the new optimal price at node 2, $P_2(q_2^{c\ (K+\Delta K)} + (K+\Delta K))$, will be smaller or equal to that before the expansion (because the consumption at node 2 must either increase or remain equal at the new optimum). Lemma 2 formally proves these facts.[15]

Lemma 2. *In the two-node network described in this section, assume that a passive/aggressive Nash equilibrium is achieved and that a passive/aggressive Nash equilibrium is still supported when making an incremental transmission investment. Then, the change in the equilibrium deargen's output due to an incremental transmission expansion is negative and smaller, in absolute value, than the change in the transmission capacity.*

Proof. Assume that the Nash equilibrium characterized by (q_1^c, q_2^c), with $q_1^c > 0$ and $q_2^c > 0$, is achieved and that a P/A Nash equilibrium is still supported when making an incremental transmission investment. Since generation firms cannot hold transmission rights, the profit of the deargen at the equilibrium is: $\pi_2^*(q_2^c, K) = q_2^c \cdot P_2(q_2^c + K) - C_2(q_2^c)$. Hence, the first order optimality condition is: $\mathrm{d}\pi_2^*/\mathrm{d}q_2^c = 0$, or equivalently: $P_2(q_2^c + K) + q_2^c \cdot P_2'(q_2^c + K) - C_2'(q_2^c) = 0$. Then, $\mathrm{d}^2(\pi_2^*(q_2^c, K))/\mathrm{d}K\mathrm{d}q_2^c = 0$, or:

$$P_2'(q_2^c * + K) \cdot \left(\frac{\mathrm{d}q_2^c *}{\mathrm{d}K} + 1\right) + \frac{\mathrm{d}q_2^c *}{\mathrm{d}K} \cdot P_2'(q_2^c * + K) + q_2^c * \cdot P_2''(q_2^c * + K) \cdot \left(\frac{\mathrm{d}q_2^c *}{\mathrm{d}K} + 1\right) - C_2''(q_2^c *) \cdot \frac{\mathrm{d}q_2^c *}{\mathrm{d}K} = 0 \tag{9}$$

or equivalently:

$$\frac{\mathrm{d}q_2^c *}{\mathrm{d}K} = \frac{-P_2'(q_2^c * + K) - q_2^c * \cdot P_2''(q_2^c * + K)}{2 \cdot P_2'(q_2^c * + K) + q_2^c * \cdot P_2''(q_2^c * + K) - C_2''(q_2^c *)}. \tag{10}$$

Since $q_2^c * > 0$, costs functions are convex, and the inverse demand functions are continuous, concave, and downward sloping, every term of the numerator of the right-hand side of Eq. (10) is positive and every term of the denominator of the right-hand side of Eq. (10) is negative. Thus, $\mathrm{d}q_2^c * / \mathrm{d}K$ is negative. Furthermore, since $|2 \cdot P_2'(q_2^c * + K) + q_2^c * \cdot P_2''(q_2^c * + K) - C_2''(q_2^c *)| > |-P_2'(q_2^c * + K) - q_2^c * \cdot P_2''(q_2^c * + K)|$, we have

[14] Recall that the two-node network used here assumes a single transmission line of thermal capacity K and that there is only one generation firm at each node, having unlimited generation capacity. We also assume that the production cost functions of the two firms are convex and twice differentiable in the firms' outputs. We also assume that the inverse demand function at each node of the network is continuous and downward sloping. Moreover, we suppose that, if the two markets were completely isolated (i.e., no connected by any transmission line), the generation firms would produce outputs q_1^M and q_2^M such that $P_1(q_1^M) < P_2(q_2^M)$.

[15] An intuitive way to understand the results proved on Lemma 2 is the following. If the deargen kept its output at the q_2^c level even after increasing the thermal capacity of the line by ΔK, the price at node 2 would decrease from $P_2(q_2^c + K)$ to $P_2(q_2^c + K + \Delta K)$, producing a lost in the deargen profit (with respect to the pre-expansion situation) equal to $q_2^c \cdot (P_2(q_2^c + K) - P_2(q_2^c + K + \Delta K))$. However, the deargen could exercise its local market power and reduce its output in order to increase the price at node 2 with respect to the theoretical price $P_2(q_2^c + K + \Delta K)$ and, thus, increase its profit with respect to the situation in which the deargen keeps the output at the q_2^c level. That is, the deargen will now act as a monopolist on the $(K+\Delta K)$-leftward-shifted inverse demand curve and reoptimize its profit by reducing its output in such a way so that the line is congested and the "gain" in profit, $q_2^{c(K+\Delta K)} \cdot (P_2(q_2^{c(K+\Delta K)} + K + \Delta K) - P_2(q_2^c + K + \Delta K))$, is larger than the lost in profit, $(q_2^c - q_2^{c(K+\Delta K)}) \cdot P_2(q_2^c + K + \Delta K)$, due to the reduction in the output with respect to the hypothetical case that the deargen keeps the output at q_2^c. Fig. 3 illustrates these facts.

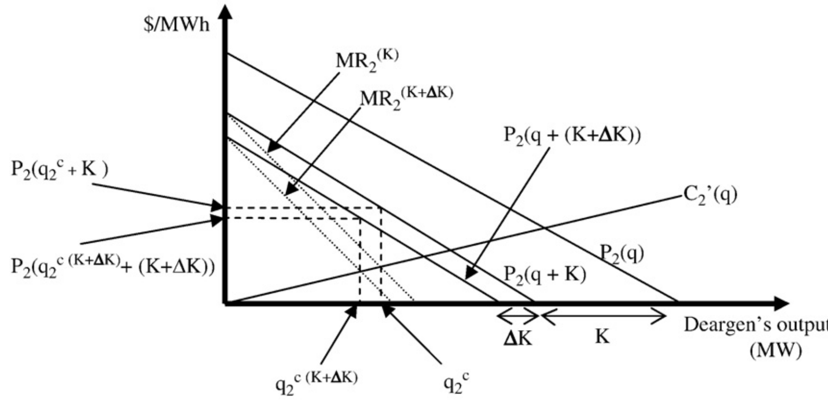

Fig. 3. Transmission investment incentives of the deargen in the two-node network.

that $|\mathrm{d}q_2{}^*/\mathrm{d}K|<1$, which implies that the change in the equilibrium deargen's output due to an incremental transmission expansion is smaller, in absolute value, than the change in the transmission capacity. □

Following Lemma 2, it becomes evident that the deargen will have disincentives to support this transmission expansion because it decreases the deargen's profit. Fig. 3 illustrates this situation (where $MR_2^{(K)}$ represents the marginal revenue when the deargen faces the K-leftward-shifted inverse demand curve and $MR_2^{(K+\Delta K)}$ corresponds to the marginal revenue when the deargen faces the $(K+\Delta K)$-leftward-shifted inverse demand curve). Proposition 2 summarizes this intuitive result.

Proposition 2. *Assume that generation firms cannot hold transmission rights. In the two-node network described in this section, the net importer generation firm (i.e., the deargen) has disincentives to support an increase in the transmission capacity up to any level such that a passive/aggressive Nash equilibrium is still supported.*

Proof. Assume that the Nash equilibrium characterized by (q_1^c, q_2^c), with $q_1^c>0$ and $q_2^c>0$, is achieved and that a P/A Nash equilibrium is still supported when making an incremental transmission investment. Since generation firms cannot hold transmission rights, the profit of the deargen at the equilibrium is: $\pi_2^*\,(q_2^c, K)=q_2^c\cdot P_2(q_2^c+K)-C_2(q_2^c)$.

By using the envelope theorem, we obtain:

$$\frac{\mathrm{d}(\pi_2{}^*(q_2^c,K))}{\mathrm{d}K}=q_2^cP_2'\cdot(q_2^c+K)\cdot(+1)=q_2^c\cdot P_2'(q_2^c+K). \quad (11)$$

Since $q_2^c>0$ and the inverse demand functions are continuous and downward sloping (i.e., $P_2'(q_2^c+K)<0$), we have from Eq. (11) that: $\mathrm{d}(\pi_2{}^*(q_2^c, K))/\mathrm{d}K<0$. This is, the equilibrium deargen's profit decreases as the transmission capacity increases, as long as a P/A Nash equilibrium is still supported. Consequently, the deargen has disincentives to support an increase in the transmission capacity up to any level such that a P/A Nash equilibrium is still supported. □

Summarizing, when the equilibrium characterized by (q_1^c, q_2^c) is accomplished, the cheapgen has incentives to support an increase in the capacity of the transmission line by some small positive amount (such that the P/A Nash equilibrium is still supported) while the deargen has disincentives to support such a transmission expansion. However, this analysis is only valid for small incremental expansions of the line. As the size of the line upgrade increases, the P/A Nash equilibrium may no longer be supported (i.e., the best response of the deargen could be to increase significantly its output so that it either decongests the line or congests the line with net flow in the opposite direction). If this occurred, then it is unclear whether the cheapgen would still have incentives to support the expansion of the transmission line. In fact, if the network upgrade were large enough so that it led to an unconstrained Nash–Cournot duopoly equilibrium, then such an investment would likely reduce the profits of both generators.[16] All these results are illustrated through a simple numerical example, presented in Section 4.1, where demand functions are linear and generation firms have constant marginal costs.

A remaining question in our analysis is what happens with the generation firms' incentives to support incremental social-welfare-improving transmission expansions when the line capacity is neither too small nor too high (i.e., when K is such that $Min\{K',K^*\}<K<Max\{K',K^*\}$). Such analysis is complex because the existence of a pure-strategy Nash equilibrium is not guaranteed in this case. Although we leave this analysis as future work, our intuition is that, even under mixed-strategy Nash–Cournot equilibria, expected nodal prices will decline as the line capacity increases. With a very small transmission capacity, for instance, nodal prices should be very close to the monopoly levels. If they were not, then either firm could improve its expected profit by simply admitting imports of K and producing the optimal passive output as a pure strategy. With K near K^*, the lower bounds on prices provided by the optimal passive output responses should be much weaker and the mixed strategy would be more likely to result in lower expected prices.

3.2. Scenario II: generation firms can hold FTRs

Assume now that generation firms can hold some FTRs. In particular, suppose that the cheapgen and the deargen hold fractions α and $(1-\alpha)$ of the K FTRs available from node 1 to node 2 ($\alpha\in[0,1]$), respectively. Thus, in our two-node network, the cheapgen now maximizes the following profit function (making rational expectations of the deargen's outcome):

$$\pi_1(q_1,\alpha)=q_1\cdot P_1(q_1-q_t)-C_1(q_1)+\alpha\cdot K\cdot[P_2(q_2+q_t)-P_1(q_1-q_t)]. \quad (12)$$

Likewise, the deargen now maximizes the following profit function (making rational expectations of the cheapgen's outcome):

$$\pi_2(q_2,\alpha)=q_2\cdot P_2(q_2+q_t)-C_2(q_2)+(1-\alpha)\cdot K\cdot[P_2(q_2+q_t)-P_1(q_1-q_t)]. \quad (13)$$

Generation firms must acquire their FTRs through some type of allocation scheme or auction. In this section, we assume that FTRs are allocated free of charge directly to the market participants.[17]

[16] If the two markets are comparable and the two firms have similar generation costs, then we obtain the well-known result that a large enough investment that "moves" the pure-strategy Nash equilibrium from a P/A Nash equilibrium to an unconstrained Nash–Cournot duopoly equilibrium reduces the profits of both generators because nodal prices "discontinuously jump down" (although firms' outputs increase).

[17] In some areas, FTRs are auctioned off among the market participants and, then, the revenues collected from the auction process are allocated to the load on a prorate basis. In contrast, in some other areas, FTRs are allocated directly free of charge to the market participants (on the basis of claims). This last scheme is the one assumed in this article.

If the transmission line capacity were high enough (i.e., $K > Max\{K', K^*\}$)[18] so that an unconstrained Nash–Cournot duopoly equilibrium would exist (and it would correspond to the unique pure-strategy Nash equilibrium), then there would be no congestion at the equilibrium. This means that the nodal prices at both ends of the uncongested line would be equal. Accordingly, all FTRs would become worthless due to the zero nodal price difference. Consequently, when the transmission line capacity is high enough, so that there is no congestion at the Nash equilibrium, the fact that generation firms can hold FTRs does not make any difference in profits as compared to the benchmark case (without FTRs). Thus, in this case, the unconstrained Nash–Cournot duopoly equilibrium is characterized by the same system of equations (first order optimality conditions) as in the benchmark case, i.e. Eqs. (1)–(5). As we mentioned in the case without FTRs, this is not an interesting case to analyze from the point of view of the transmission investment incentives because generation firms have obviously no incentives to support an increment in the capacity of a line that has excess capacity.

On the other hand, if the transmission line capacity were low enough (i.e., $K < Min\{K', K^*\}$) so that a P/A Nash equilibrium were supported, then the transmission line would be congested with net flow from node 1 to node 2 (i.e., $q_t = K$) at the unique pure-strategy Nash equilibrium.[19] In this case, we can analyze the incentives/disincentives that the generation firms have to support an increase in the capacity of the transmission line, while a P/A Nash equilibrium is still supported, in a similar way as in the benchmark case (without FTRs).

When the P/A Nash equilibrium is supported, the cheapgen maximizes its profit as if it had monopoly power over its K-rightward-shifted inverse demand function, but having two revenues streams now: a first stream of revenue from sales of energy and a second stream of revenues from the congestion rents from the FTRs. Consequently, while the P/A Nash equilibrium prevails, the cheapgen effectively increases the price elasticity of its residual demand curve by holding FTRs.[20] Proposition 3 establishes the same result as in Proposition 1 in the case that generation firms can hold FTRs. This is, in the two-node network described in this section, the cheapgen has positive incentives to support an increase in the transmission capacity up to any level so that a P/A Nash equilibrium is still supported.

Proposition 3. *In the two-node network described in this section, the net exporter generation firm (i.e., the cheapgen) has positive incentives to support an increase in the transmission capacity up to any level so that a passive/aggressive Nash equilibrium is still supported.*

Proof. When assuming that generation firms cannot hold transmission rights, the proof is identical to the proof of Proposition 1. Now, assume generation firms can hold FTRs. Suppose that the cheapgen and the deargen hold fractions α and $(1-\alpha)$ of the K FTRs available from node 1 to node 2 (α [0,1]), respectively.

Assume that a Nash equilibrium characterized by $(q_1^c(\alpha), q_2^c(\alpha))$, with $q_1^c(\alpha) > 0$ and $q_2^c(\alpha) > 0$, is achieved and that a P/A Nash equilibrium is still supported when making an incremental transmission investment. The profit of the cheapgen at the equilibrium is:

$$\pi_1^*(q_1^c(\alpha), K) = q_1^c(\alpha) \cdot P_1(q_1^c(\alpha) - K) - C_1(q_1^c(\alpha)) + \alpha \cdot K \cdot [P_2(q_2^c(\alpha) + K) - P_1(q_1^c(\alpha) - K)]. \tag{14}$$

By using the envelope theorem, we obtain:

$$\frac{\mathrm{d}(\pi_1^*(q_1^c(\alpha), K))}{\mathrm{d}K} = -q_1^c(\alpha) \cdot P'_1(q_1^c(\alpha) - K) + \alpha \cdot [P_2(q_2^c(\alpha) + K) - P_1(q_1^c(\alpha) - K)] + \alpha \cdot K \cdot P'_1(q_1^c(\alpha) - K),$$

or equivalently:

$$\frac{\mathrm{d}(\pi_1{}^*(q_1^c(\alpha), K))}{\mathrm{d}K} = -[q_1^c(\alpha) - \alpha \cdot K] \cdot P'_1(q_1^c(\alpha) - K) + \alpha \cdot [P_2(q_2^c(\alpha) + K) - P_1(q_1^c(\alpha) - K)]. \tag{15}$$

Since $q_1^c(\alpha) > K > \alpha \cdot K$ in the P/A Nash equilibrium (because the cheapgen is exporting power and the line is congested) and the inverse demand functions are continuous and downward sloping, the first term of the right-hand side of Eq. (15) is positive. The second term is also positive because the equilibrium price at node 2 must be greater than the equilibrium price at node 1 in order to have power flowing from node 1 to node 2 in the P/A equilibrium (otherwise, if $P_2(q_2^c(\alpha) + K) < P_1(q_1^c(\alpha) - K)$), it obviously would be more profitable for the deargen to act more aggressively than just producing the passive response of the P/A equilibrium). Consequently, from Eq. (15), we get that: $\mathrm{d}(\pi_1^*(q_1^c(\alpha), K)) / \mathrm{d}K > 0$. That is, the equilibrium cheapgen's profit increases as the transmission capacity increases, as long as a P/A Nash equilibrium is still supported. Consequently, the cheapgen has positive incentives to support an increase in the transmission capacity up to any level so that a P/A Nash equilibrium is still supported. □

Now, we are interested in studying the behavior of the cheapgen's incentives for supporting a line expansion (as discussed in Propositions 1 and 3) when the cheapgen changes its share of FTRs. In order to do this, we previously need to analyze the behavior of both the optimal cheapgen's output and the optimal cheapgen's profit with respect to changes in the cheapgen's share of FTRs.

The optimal cheapgen's output, $q_1^c{}^*(\alpha)$, is increasing continuously in α, from $q_1^c{}^*(0)$ (benchmark case) to $q_1^c{}^*(1)$. This monotonicity is based on the rationale that, the more generation firms internalize the congestion rents, the higher the congestion rents are due to the firms' ability to influence nodal prices. As the fraction of FTRs that the cheapgen holds increases, the cheapgen is more likely to sacrifice some profits it would otherwise earn from supplying energy in order to increase the profits it receives in the form of dividends on the FTRs it holds. Accordingly, while the P/A Nash equilibrium is supported, the larger α, the stronger the cheapgen's incentive to increase its production (and, in this way, decrease the price at node 1, for the benefit of the consumers located at node 1) in order to raise its equilibrium profit. Consequently, the equilibrium cheapgen's profit is increasing in α. These results are summarized in Lemma 3.

Lemma 3. *In the two-node network described in this section, assume that a passive/aggressive Nash equilibrium is supported. Suppose also that the cheapgen holds fraction α of the K FTRs available from node 1 to node 2 ($\alpha \in [0,1]$). Then, the change in the equilibrium cheapgen's output due to an increase in the cheapgen's share of FTRs is positive and smaller than the product between the transmission capacity and the increase in the cheapgen's share of FTRs (i.e., $0 < dq_1^c{}^* / d\alpha < K$). Moreover, the change in the equilibrium cheapgen's profit due to an increase in the cheapgen's share of FTRs is positive (i.e., $d\pi_1^* / d\alpha > 0$).*

[18] Here, we maintain the same notation as in the case without FTRs. That is, K' corresponds to the largest line capacity that can support a P/A Nash equilibrium and K^* represents the smallest line capacity that can support an unconstrained Nash-Cournot duopoly equilibrium.

[19] The proof that the outcome $(q_1^c(\alpha), q_2^c(\alpha))$, which maximizes the generation firms' profits given both that the line is congested with flow from node 1 to node 2 and that α has a fixed value, is a Nash equilibrium is analogous to the case without FTRs.

[20] When holding FTRs on the congested line, the cheapgen has incentive to increase the nodal price difference. To do that, it would increase its output and, thus, decrease its nodal price with respect to the benchmark (no FTRs)-case levels. Accordingly, at the profit-maximizing output, $P_1(q_1^c - K)$ would be lower (and $q_1^c - K$ would be higher) when $\alpha > 0$ (holding FTRs) than when $\alpha = 0$ (without FTRs). Thus, since demand is downward sloping, we would have that $\frac{P_1(q_1^c - K)}{(q_1^c - K) \cdot P'_1(q_1^c - K)}$ — which corresponds to the price elasticity of the residual demand curve — is less negative (i.e., less inelastic) when $\alpha > 0$ (holding FTRs) than when $\alpha = 0$ (without FTRs).

Proof. Assume that the Nash equilibrium characterized by $(q_1^c(a), q_2^c(a))$, with $q_1^c(a)>0$ and $q_2^c(a)>0$, is achieved. Since generation firms can hold transmission rights, the profit of the cheapgen at the equilibrium is given by Eq. (14). Hence, the first order optimality condition is: $d\pi_1^*/dq_1^c=0$, or equivalently: $P_1(q_1^c-K)+q_1^c\cdot P_1'(q_1^c-K)-C_1'(q_1^c)-\alpha\cdot K\cdot P_1'(q_1^c-K)=0$. Then, $d^2(\pi_1^*(q_1^c(\alpha),K))/d\alpha\, dq_1^c=0$, or:

$$P_1'(q_1^{c*}-K)\cdot\frac{dq_1^{c*}}{d\alpha}+\frac{dq_1^{c*}}{d\alpha}\cdot P_1'(q_1^{c*}-K)+q_1^{c*}\cdot P_1''(q_1^{c*}-K)\cdot\frac{dq_1^{c*}}{d\alpha}$$
$$-C_1''(q_1^{c*})\cdot\frac{dq_1^{c*}}{d\alpha}-K\cdot P_1'(q_1^{c*}-K)$$
$$-\alpha\cdot K\cdot P_1''(q_1^{c*}-K)\cdot\frac{dq_1^{c*}}{d\alpha}=0$$

or equivalently:

$$\frac{dq_1^{c*}}{d\alpha}=\frac{K\cdot P_1'(q_1^{c*}-K)}{2\cdot P_1'(q_1^{c*}-K)+(q_1^{c*}-\alpha\cdot K)\cdot P_1''(q_1^{c*}-K)-C_1''(q_1^{c*})}. \tag{16}$$

Since $q_1^{c*}>K>\alpha\cdot K$ in the P/A Nash equilibrium, costs functions are convex, and the inverse demand functions are continuous, concave, and downward sloping, every term of both the numerator and the denominator of the right-hand side of Eq. (16) is negative. Thus, $dq_1^{c*}/d\alpha$ is positive. Furthermore, since $|2\cdot P_1'(q_1^{c*}-K)+(q_1^{c*}-\alpha\cdot K)\cdot P_1''(q_1^{c*}-K)-C_1''(q_1^{c*})|>|P_1'(q_1^{c*}-K)|$, we have that $dq_1^{c*}/d\alpha<K$. Moreover, by using Eq. (14) and the envelope theorem, we get that:

$$\frac{d(\pi_1^*(q_1^c(\alpha),K))}{d\,\alpha}=K\cdot\left[P_2(q_2^c(\alpha)+K)-P_1(q_2^c(\alpha)+K)\right]. \tag{17}$$

The right-hand side of Eq. (17) is positive because the equilibrium price at node 2 must be greater than the equilibrium price at node 1 in order to have power flowing from node 1 to node 2 in the P/A equilibrium. Consequently, $d\pi_1^*/d\alpha>0$. □

Now, we use Lemma 3 to prove Proposition 4, which establishes that, while a passive/aggressive Nash equilibrium prevails, the more FTRs the cheapgen holds, the more incentive it has to support an incremental transmission expansion.

Proposition 4. *In the two-node network described in this section, assume that a passive/aggressive Nash equilibrium is achieved and that a passive/aggressive Nash equilibrium is still supported when making an incremental transmission investment. Moreover, assume generation firms can hold FTRs. If the transmission capacity is sufficiently small, then the change in the equilibrium cheapgen's profit due to an incremental transmission expansion is increasing in the fraction of FTRs that the cheapgen holds (i.e., $d\pi_1^*/dK$ is increasing in α).*

Proof. Assume that generation firms can hold FTRs. Suppose that the cheapgen and the deargen hold fractions α and $(1-\alpha)$ of the K FTRs available from node 1 to node 2 ($\alpha\in[0,1]$), respectively. Assume that a Nash equilibrium characterized by $(q_1^c(\alpha), q_2^c(\alpha))$, with $q_1^c(\alpha)>0$ and $q_2^c(\alpha)>0$, is achieved and that a P/A Nash equilibrium is still supported when making an incremental transmission investment.

Using Eq. (15) to take derivative of the function $d\pi_1^*/d\,K$ with respect to α, we obtain:

$$\frac{d}{d\alpha}\left(\frac{d(\pi_1^*(q_1^c(\alpha),K))}{dK}\right)=-\left[\frac{dq_1^{c*}}{d\alpha}-K\right]\cdot P_1'(q_1^{c*}-K)-\left[q_1^{c*}-\alpha\cdot K\right]$$
$$\cdot P_1''(q_1^{c*}-K)\cdot\frac{dq_1^{c*}}{d\alpha} \tag{18}$$
$$+\left[P_2(q_2^{c*}+K)-P_1(q_1^{c*}-K)\right]-\alpha\cdot P_1'(q_1^{c*}-K)\cdot\frac{dq_1^{c*}}{d\alpha}$$

From Lemma 3, we know that $dq_1^{c*}/d\alpha$ is positive. Thus, considering that (i) $q_1^{c*}>\alpha\cdot K$ in the P/A Nash equilibrium, (ii) the inverse demand functions are continuous, concave, and downward sloping, and (iii) the equilibrium price at node 2 must be greater than the equilibrium price at node 1 in order to have power flowing from node 1 to node 2 in the P/A equilibrium, we conclude that all terms of the right-hand side of Eq. (18) other than the first one are positive. Unfortunately, the first term of the right-hand side of Eq. (18) is negative because $dq_1^{c*}/d\alpha<K$, as we proved in Lemma 3. Accordingly, the derivative of the function $d\pi_1^*/d\,K$ with respect to α, will be positive if the absolute value of the first term of the right-hand side of Eq. (18) is smaller than the sum of the other terms, which is likely to happen. A sufficient condition for this is that the transmission capacity, K, is sufficiently small so that the right-hand side of Eq. (18) is positive, which implies that $d\pi_1^*/d\,K$ is increasing in α. □

The previous propositions assume that FTRs are allocated free of charge directly to the generation firms. If generation firms must acquire their FTRs through some type of auction, the auctioneer could sell the FTRs created by a transmission expansion to the cheapgen up to a price such that the extra expenditure incurred to acquire the FTRs equals the difference in the cheapgen's profit between before and after the expansion. In such a case, and assuming that an increase in the transmission capacity would increase both the total consumer surplus and the social welfare (Sheffrin, 2005), it would be possible to leave the cheapgen revenue neutral and, at the same time, improve both consumer surplus and social welfare. This would mean that we could use this type of incentive as an instrument to induce incremental transmission expansions that are social-welfare improving. Proposition 5 summarizes this result.

Proposition 5. *In the two-node network described in this section, assume that a passive/aggressive Nash equilibrium is achieved and that a passive/aggressive Nash equilibrium is still supported when making an incremental transmission investment. Assume also that generation firms can hold FTRs. Moreover, assume that an increase in the transmission capacity would increase both consumer surplus and social welfare. If all FTRs were auctioned off to the net exporter generation firm, then it is possible to increase both consumer surplus and social welfare while keeping the net exporter generation firm revenue neutral.*

Proof. Assume generation firms can hold FTRs, which must be acquired through some type of auction. Suppose that an incremental transmission expansion is desired in the described two-node network because it increases both consumer surplus and social welfare, as it is more likely to happen in a congested radial network according to the *gains from trade* economic principle (Sheffrin, 2005). Then, an auctioneer could sell the FTRs created by the transmission expansion to the cheapgen for a price such that the extra expenditure incurred to acquire the FTRs equals the difference in the cheapgen's profit between before and after the expansion (Proposition 3 ensures that the cheapgen's profit increases within this expansion). Then, Proposition 5 is true by construction, which implies that this type of incentives can be used as an instrument to induce “desired” incremental transmission expansions, leaving the net exporter generation firm revenue neutral. □

On the other hand, while a P/A Nash equilibrium is still supported, the deargen maximizes its profit as if it had monopoly power over its K-leftward-shifted inverse demand function, but having now also two revenues streams: a first stream of revenue from energy sales and a second revenue stream from the congestion rents. As the fraction of FTRs that the deargen holds increases, the deargen is more likely to sacrifice some profits it would otherwise earn from supplying energy in order to increase the profits it receives in the form of dividends on the FTRs it holds. Accordingly, while the P/A Nash equilibrium prevails, the smaller α, the stronger the deargen's incentives to decrease its production and, in this way, increase the price at node 2. Consequently, while the P/A Nash equilibrium prevails, the deargen effectively reduces the price elasticity of its residual demand curve and increases its local market power by holding FTRs.

Proposition 6 states a similar result as in Proposition 2 in the case that generation firms can hold FTRs. In this case, the deargen's incentives to support an increase in the transmission capacity are uncertain.

Proposition 6. *Assume generation firms can hold FTRs. In the two-node network described in this section, while a passive/aggressive Nash equilibrium prevails, the incentives that the net importer generation firm (i.e., the deargen) has to support an increase in the transmission capacity are ambiguous.*

Proof. Assume generation firms can hold FTRs. Suppose that the cheapgen and the deargen hold fractions α and $(1-\alpha)$ of the K FTRs available from node 1 to node 2 ($\alpha\in[0,1]$), respectively.

Assume that a Nash equilibrium characterized by $(q_1^c(\alpha), q_2^c(\alpha))$, with $q_1^c(\alpha)>0$ and $q_2^c(\alpha)>0$, is achieved and that a P/A Nash equilibrium is still supported when making an incremental transmission investment. The profit of the deargen at the equilibrium is:

$$\pi_2^*(q_2^c(\alpha),K) = q_2^c(\alpha)\cdot P_2(q_2^c(\alpha)+K) - C_2(q_2^c(\alpha)) + (1-\alpha) \cdot K\cdot[P_2(q_2^c(\alpha)+K) - P_1(q_2^c(\alpha)-K)]. \tag{19}$$

By using the envelope theorem, we obtain:

$$\frac{\mathrm{d}(\pi_2^*(q_2^c(\alpha),K))}{\mathrm{d}\,K} = q_2^c(\alpha)\cdot P_2'(q_2^c(\alpha)+K) + (1-\alpha) \cdot[P_2(q_2^c(\alpha)+K) - P_1(q_1^c(\alpha)-K)] + (1-\alpha)\cdot K\cdot P_2'(q_2^c(\alpha)+K),$$

or equivalently:

$$\frac{\mathrm{d}(\pi_2^*(q_2^c(\alpha),K))}{\mathrm{d}\,K} = [q_2^c(\alpha)+(1-\alpha)\cdot K]\cdot P_2'(q_2^c(\alpha)+K) + (1-\alpha) \cdot[P_2(q_2^c(\alpha)+K) - P_1(q_1^c(\alpha)-K)]. \tag{20}$$

Since $q_2^c(\alpha)>0$ and the inverse demand functions are continuous and downward sloping, the first term of the right-hand side of Eq. (20) is negative. The second term is positive because the equilibrium price at node 2 must be greater than the equilibrium price at node 1 in order to have power flowing from node 1 to node 2 in the P/A equilibrium. Consequently, according to Eq. (20), we cannot guarantee the sign of $\mathrm{d}(\pi_2^*(q_2^c(\alpha), K))/\mathrm{d}\,K$. This sign will be negative if the energy-sales revenue stream is stronger than the revenue stream from the congestion rents and positive in the opposite case. Thus, while a P/A Nash equilibrium prevails, the incentive that the deargen has to support an increase in the transmission capacity is ambiguous. □

Additionally, as we did in the case of the cheapgen, we can use Eq. (20) to argue about the monotonicity of $\mathrm{d}\pi_2^*/\mathrm{d}\,K$ with respect to α. This result is summarized in Proposition 7.

Proposition 7. *In the two-node network described in this section, assume that a passive/aggressive Nash equilibrium is achieved and that a passive/aggressive Nash equilibrium is still supported when making an incremental transmission investment. Moreover, assume that generation firms can hold FTRs. If the transmission capacity is sufficiently small, then the change in the equilibrium deargen's profit due to an incremental transmission expansion is decreasing in the fraction of FTRs that the cheapgen holds (i.e., $\mathrm{d}\pi_2^*/\mathrm{d}K$ is decreasing in α).*

Proof. Assume generation firms can hold FTRs. Suppose that the cheapgen and the deargen hold fractions α and $(1-\alpha)$ of the K FTRs available from node 1 to node 2 ($\alpha\in[0,1]$), respectively. Assume that a Nash equilibrium characterized by $(q_1^c(\alpha), q_2^c(\alpha))$, with $q_1^c(\alpha)>0$ and $q_2^c(\alpha)>0$, is achieved and that a P/A Nash equilibrium is still supported when making an incremental transmission investment.

Using Eq. (20) to take derivative of the function $\mathrm{d}\pi_2^*/\mathrm{d}K$ with respect to α, we obtain:

$$\frac{\mathrm{d}}{\mathrm{d}\alpha}\left(\frac{\mathrm{d}(\pi_2^*(q_2^c(\alpha),K))}{\mathrm{d}K}\right) = \left[\frac{\mathrm{d}q_2^{c*}}{\mathrm{d}\alpha} - K\right]\cdot P_2'(q_2^{c*}+K) + [q_2^{c*}+(1-\alpha)\cdot K] \cdot P_2''(q_2^{c*}+K)\cdot\frac{\mathrm{d}q_2^{c*}}{\mathrm{d}\alpha} - [P_2(q_2^{c*}+K) - P_1(q_1^{c*}-K)] + (1-\alpha)\cdot P_2'(q_2^{c*}+K)\cdot\frac{\mathrm{d}q_2^{c*}}{\mathrm{d}\alpha} \tag{21}$$

In the same way of Lemma 3, it is easy to prove that $0<\mathrm{d}q_2^{c*}/\mathrm{d}\alpha<K$. Thus, considering that (i) $q_2^{c*}>0$, (ii) the inverse demand functions are continuous, concave, and downward sloping, and (iii) the equilibrium price at node 2 must be greater than the equilibrium price at node 1 in order to have power flowing from node 1 to node 2 in the P/A equilibrium, we conclude that all terms of the right-hand side of Eq. (21) other than the first one are negative. The first term of the right-hand side of Eq. (21) is positive because $\mathrm{d}q_2^{c*}/\mathrm{d}\alpha<K$. Accordingly, the derivative of the function $\mathrm{d}\pi_2^*/\mathrm{d}K$ with respect to α, will be negative if the first term of the right-hand side of Eq. (21) is smaller than the absolute value of the sum of the other terms, which is likely to happen. A sufficient condition for this is that the transmission capacity, K, is sufficiently small so that the right-hand side of Eq. (21) is negative, which implies that $\mathrm{d}\pi_2^*/\mathrm{d}K$ is decreasing in α. □

Proposition 6 says that we cannot guarantee that the deargen's profit increases when an incremental social-welfare-improving transmission expansion occurs and, thus, we cannot guarantee that the deargen has the correct incentives to support such an expansion. Furthermore, Proposition 7 tells us that, even if the deargen has the right incentives to support an incremental social-welfare-improving transmission expansion, those incentives would likely decrease as more FTRs are allocated to the cheapgen (i.e., as α increases). Therefore, although allocating FTRs to the net exporter generation firm can increase its incentives to support a social-welfare-improving transmission expansion, such a policy would dilute the net-importer-generation-firm's incentives to support the capacity expansion. Consequently, a socially concerned regulator who wants to align the incentives for transmission expansion of the society and of the net exporter firm must be aware that allocating FTRs to the net exporter firm would also increase the opposition of the net importer generation firm to support the expansion.

Finally, we like to reiterate, that the analysis in this-section is only valid for sufficiently small transmission upgrades such that the transmission line capacity does not exceed K'. However, the value of K' increases as α increases. Thus, under this second scenario, both generation firms will support a passive/aggressive Nash equilibrium up to a line capacity that not only exceeds the benchmark case threshold, but is even larger as more FTRs are allocated to the cheapgen.

4. Numerical example

In this section, we use the same numerical example employed in Section 2 to illustrate the previous-section findings about the incentives that generation firms have to support incremental social-welfare-improving transmission expansions under both scenarios: with and without FTRs.

This is, under both scenarios, we assume that the inverse demand functions are given by $P_1(q) = 100 - 0.1\cdot q$ at node 1 and $P_2(q) = 120 - 0.2\cdot q$ at node 2 (in \$/MWh) and that the marginal costs of generation are zero for the cheapgen and \$20/MWh for the deargen. We also assume now that there is a transmission line connecting both nodes.

4.1. Scenario I: generation firms cannot hold transmission rights

If the capacity of the line linking both nodes were very high, then the transmission capacity constraint would not be binding and the

Table 2
Equilibria in the two-node network, without considering FTRs.

Equilibrium with $K=50$ MW	Equilibrium with $K=52$ MW	Equilibrium with $K>115$ MW
$q_1=525$ MWh	$q_1=526$ MWh	$q_1=633.33$ MWh
$q_2=225$ MWh	$q_2=224$ MWh	$q_2=333.33$ MWh
$P_1=\$52.5$/MWh	$P_1=\$52.6$/MWh	$P_1=\$42.2$/MWh
$P_2=\$65$/MWh	$P_2=\$64.8$/MWh	$P_2=\$42.2$/MWh
$\Pi_1=\$27{,}563$/h	$\Pi_1=\$27{,}668$/h	$\Pi_1=\$26{,}741$/h
$\Pi_2=\$10{,}125$/h	$\Pi_2=\$10{,}035$/h	$\Pi_2=\$7{,}407$/h
$CS_1=\$11{,}281$/h	$CS_1=\$11{,}234$/h	$CS_1=\$16{,}691$/h
$CS_2=\$7{,}563$/h	$CS_2=\$7{,}618$/h	$CS_2=\$15{,}123$/h
$W=\$56{,}531$/h	$W=\$56{,}554$/h	$W=\$65{,}963$/h

CS_i denotes to the consumer surplus at node i and W denotes the total social welfare (not accounting for transmission investment costs).

Table 3
Equilibria in the two-node network, when $\alpha=0.8$.

Equilibrium with $K=50$ MW	Equilibrium with $K=52$ MW
$q_1=545$ MWh	$q_1=546.8$ MWh
$q_2=220$ MWh	$q_2=218.8$ MWh
$P_1=\$50.5$/MWh	$P_1=\$50.5$/MWh
$P_2=\$66$/MWh	$P_2=\$65.8$/MWh
$\pi_1=\$28{,}143$/h	$\pi_1=\$28{,}262$/h
$\pi_2=\$10{,}275$/h	$\pi_2=\$10{,}189$/h
$CS_1=\$12{,}251$/h	$CS_1=\$12{,}241$/h
$CS_2=\$7{,}290$/h	$CS_2=\$7{,}333$/h
$W=\$57{,}959$/h	$W=\$58{,}025$/h

CS_i denotes the consumer surplus at node i and W denotes the total social welfare (not accounting for transmission investment costs).

firms would compete as Cournot duopolists in the combined market. In such a case, at the unique pure-strategy Nash equilibrium, the cheapgen would hourly produce 633 MWh while the deargen would hourly generate 333 MWh and the market-clearing price would be \$42.2/MWh at both nodes.

The smallest transmission capacity that can support an unconstrained Nash–Cournot duopoly equilibrium, K^*, is approximately equal to 115 MW in this numerical example.[21] With $K=K^*$, the deargen is indifferent between producing its unconstrained Nash–Cournot equilibrium hourly output (i.e., 333 MWh) and producing its optimal passive response (i.e., 193 MWh), given that the cheapgen is producing 633 MWh (i.e., its unconstrained Nash–Cournot equilibrium hourly output). At any larger K, each generation firm would strictly prefer the unconstrained Nash–Cournot duopoly equilibrium outcome to its optimal passive output response when the other firm produces its unconstrained Nash–Cournot equilibrium quantity.

For a transmission line of capacity slightly less than K^*, $K=110$ MW for instance, the unconstrained Nash–Cournot equilibrium is not attainable; the deargen would (just barely) prefer to produce the optimal passive output than play its Cournot best response to the cheapgen producing its Nash–Cournot equilibrium quantity. But if the deargen produced its optimal passive output (i.e., 195 MWh), then the cheapgen would revert to sell its profit-maximizing quantity that congests the transmission line (i.e., 555 MWh). This amount is smaller than the cheapgen's Nash–Cournot equilibrium quantity (i.e., 633 MWh). As the cheapgen reduces its output, producing its optimal passive output becomes less attractive to the deargen. If that were the case, then the deargen would jump to produce its Cournot best response to 555 MWh, which is 373 MWh. With the line uncongested, however, the cheapgen would then respond with its Cournot best response of 614 MWh, and the process would once again iterate toward the unconstrained Nash–Cournot equilibrium. However, because the line capacity is just slightly below the level that can support the Nash–Cournot equilibrium, as the cheapgen's output approaches its Nash–Cournot equilibrium quantity (i.e., 633 MWh), and strictly before it equals that quantity, the deargen will once again revert to produce its optimal passive output. Consequently, no pure-strategy Nash equilibrium exists in this case. This situation will occur for any line capacity between K' and K^*.

The largest line capacity that can support a P/A Nash equilibrium, K', is approximately equal to 53.6 MW in this numerical example.[22] With $K=K'$, the deargen is indifferent between producing its Cournot best response to the cheapgen's aggressive output and producing its optimal passive output. At any smaller K, each generation firm would strictly prefer the P/A Nash equilibrium outcome to its Cournot best response when the other firm produces its P/A Nash equilibrium quantity.

Summarizing, for a line of capacity smaller than 53.6 MW (i.e., for K such that $0<K<K'$), the P/A Nash equilibrium characterized by $q_1^c=5\cdot(100+0.1\cdot K)$ and $q_2^c=2.5\cdot(100-0.2\cdot K)$ exists and is the unique pure-strategy Nash equilibrium; for a line of capacity between 53.6 MW and 115 MW (i.e., $K'<K<K^*$), no pure-strategy Nash equilibrium exists; and for a line of capacity higher than 115 MW (i.e., $K^*<K$), the unconstrained Nash–Cournot equilibrium characterized by $q_1^{\mathrm{UCDE}}=633$ MWh and $q_2^{\mathrm{UCDE}}=333$ MWh is the unique pure-strategy Nash equilibrium.

Now, suppose that the capacity of the transmission line connecting the cheapgen and the deargen is currently 50 MW. With this transmission capacity, the resulting equilibrium will be the one shown in the first column of Table 2.

If the capacity of the transmission line were increased by a large-enough amount such that it became greater than K^*, then the transmission capacity constraint would not be binding and the firms would compete as Cournot duopolists in the combined market. As result of that, the cheapgen would earn a profit of \$26,741/h and the deargen would earn a profit of \$7,407/h, which would result in a reduction in profits for both generation firms as compared to the pre-expansion situation. Consequently, neither the cheapgen nor the

[21] We computed K^* as follows. The deargen's profit, when a line of capacity K is congested into its market, is given by $\pi_2(q_2^c)=q_2^c\cdot P_2(q_2^c+K)-C_2(q_2^c)=q_2^c\cdot[120-0.2\cdot(q_2^c+K)]-20\cdot q_2^c=(100-0.2\cdot K)\cdot q_2^c-0.2\cdot(q_2^c)^2$, and the first order optimality condition of the deargen's profit maximization problem implies that $q_2^c{}^*=2.5\cdot(100-0.2\cdot K)$, where $q_2^c{}^*$ is the deargen's optimal passive output. Thus, the deargen's profit from producing its optimal passive output is: $\pi_2(q_2^c{}^*)=(100-0.2\cdot K)\cdot q_2^c{}^*-0.2\cdot(q_2^c{}^*)^2=0.05\cdot(500-K)^2$. Consequently, the line capacity that makes the deargen indifferent between producing its unconstrained Nash–Cournot duopoly equilibrium output, q_2^{UCDE}, and producing its optimal passive output, $q_2^c{}^*$, given that the cheapgen is producing its unconstrained Nash–Cournot duopoly equilibrium output, must satisfy the condition $\pi_2(q_2^{\mathrm{UCDE}})=\pi_2(q_2^c{}^*)$, or equivalently, $7407=0.05\cdot(500-K^*)^2$. Thus, $K^*=500-\sqrt{(7407/0.05)}\approx 115$ MW. □

[22] To compute K', we proceed as follows. The cheapgen's profit, when a line of capacity K is congested from its market, is given by $\pi_1(q_1^c)=q_1^c\cdot P_1(q_1^c-K)-C_1(q_1^c)=q_1^c-[100-0.1\cdot(q_1^c-K)]-0=(100+0.1\cdot K)\cdot q_1^c-0.1\cdot(q_1^c)^2$, and the first order optimality condition of the cheapgen's profit maximization problem implies that $q_1{}^{c*}=5\cdot(100+0.1\cdot K)$, where $q_1{}^{c*}$ is the cheapgen's optimal aggressive output. Thus, the deargen's Cournot best response to $q_1{}^{c*}$ is a quantity $q_2{}^{c(\mathrm{BR})}$ satisfying:

$$q_2^{c(\mathrm{BR})}=\mathrm{Argmax}_{\{q_2\}\overline{\pi_2}(q_2)},$$

where

$$\overline{\pi_2}(q_2)=q_2\cdot P(q_1^{c*}+q_2)-C_2(q_2)=$$
$$=q_2\cdot\left[106.67-0.067\cdot(q_1^{c*}+q_2)\right]-20\cdot q_2=$$
$$=q_2\cdot[106.67-0.067\cdot(5\cdot(100+0.1\cdot K)+q_2)]-20\cdot q_2=$$
$$=(53.3-0.033\cdot K)\cdot q_2-0.067\cdot(q_2)^2.$$

The first-order optimality condition implies that $q_2{}^{c(BR)}=0.25\cdot(1600-K)$. Thus, the deargen's profit from producing the Cournet best response to $q_1^c{}^*$ is:

$$\overline{\pi_2}(q_2^{c(BR)})=(53.3-0.033\cdot K)q_2^{c(BR)}-0.067\cdot(q_2^{c(BR)})^2=(1600-K)^2/240.$$

Consequently, the line capacity that leaves the deargen indifferent between producing its Cournot best response to the cheapgen's aggressive output (i.e., $q_2{}^{c(BR)}$) and producing its optimal passive output (i.e., $q_2{}^{c*}$) must satisfy $\overline{\pi_2}(q_2{}^{c(BR)})=\pi_2(q_2{}^{c*})$. Recalling that the deargen's profit when producing its optimal passive response to $q_1{}^{c*}$ is $\pi_2(q_2{}^{c*})=0.05\cdot(500-K)^2$, we conclude that K' must satisfy the following equality: $(1600-K')^2/240=0.05\cdot(500-K')^2$. Thus we have

$$K'=\frac{500^*\sqrt{12}-1{,}600}{\sqrt{12}-1}\approx 53.6\mathrm{MW}.$$ □

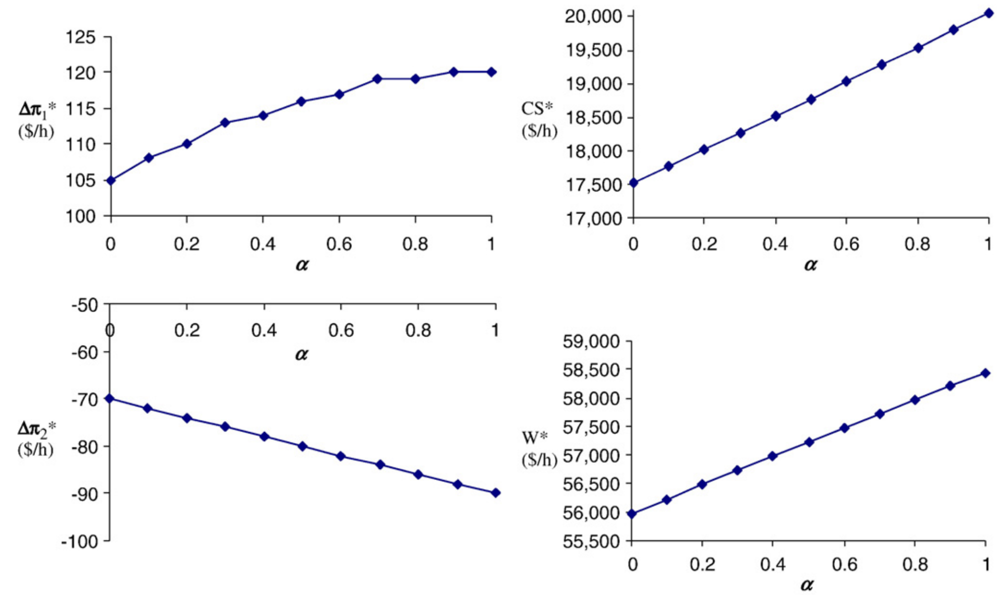

Fig. 4. Evolution of equilibrium quantities as α increases.

deargen have incentive to support such an investment, although it may improve social welfare (from \$56,531/h to \$65,963/h, without considering any investment cost).

On the other hand, if the thermal capacity of the transmission line were slightly increased from 50 MW to 52 MW (note that 52 MW $<K'$), then the resulting equilibrium would be the one shown in the second column of Table 2. Comparing the results obtained when $K=50$ MW and when $K=52$ MW, we verify that, as the transmission capacity increases from 50 MW to 52 MW: (i) the cheapgen increases its output at the equilibrium (in agreement with Lemma 1), (ii) the equilibrium price at node 1 increases, (iii) the cheapgen's profit increases (which confirms the cheapgen's incentives to support this transmission expansion), (iv) the deargen reduces its output at the equilibrium (in agreement with Lemma 2), (v) the equilibrium price at node 2 decreases, (vi) the deargen's profit decreases (which confirms the deargen's disincentives to support this transmission expansion), and (vii) social welfare increases. Consequently, these results verify that, while a P/A Nash equilibrium prevails, the cheapgen has incentives to support an increase in the capacity of the transmission line while the deargen has disincentives to support such an expansion. As mentioned before, this conclusion is only valid for upgrades that increase the capacity of the line up to K'.

4.2. Scenario II: generation firms can hold FTRs

Now, we assume that all FTRs are allocated free of charge directly to the generation firms. For illustrative purposes, suppose that the

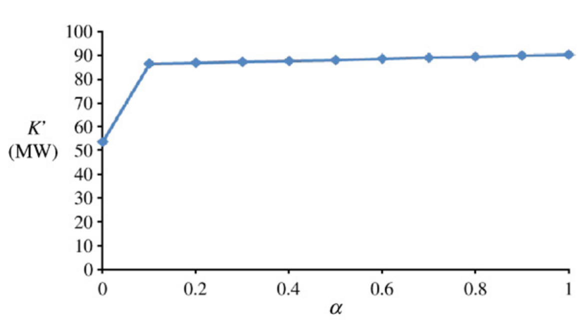

Fig. 5. Evolution of K' as α increases.

cheapgen holds 80% of the available FTRs and the deargen holds the remaining 20% (i.e., $\alpha=0.8$). In this case, Table 3 presents the resulting equilibria when the transmission capacity is 50 MW and when it is 52 MW.

By comparing Tables 2 and 3, we observe that, by holding some FTRs, both generation firms increase their profits with respect to the benchmark case. Furthermore, we notice that, when holding FTRs, the cheapgen has incentives to increase its production (and, in this way, to decrease its nodal price) while the deargen has incentives to decrease its production (and, in this way, to increase its nodal price) in order to increase their revenues from congestion rents, as we predicted in the previous section.

As in the benchmark case, by comparing the two columns of Table 3, we observe that the cheapgen has positive incentives to support an increase from 50 MW to 52 MW in the transmission capacity while the deargen has disincentives to support such an expansion. Moreover, by comparing Tables 2 and 3, we note that the change in the equilibrium cheapgen's profit due to the incremental transmission expansion is greater in the case where the cheapgen can hold FTRs (and, in fact, it is increasing in α, as shown in Fig. 4). This result suggests that, while the P/A Nash equilibrium prevails, it would be more likely that the cheapgen supports an incremental social-welfare-improving transmission expansion when it holds FTRs than when it does not hold FTRs.

By varying the values of α, it is straightforward to verify both that the larger α, the stronger the cheapgen's incentive to increase its production (and, in this way, to decrease its nodal price). Furthermore, the larger α, the weaker the deargen's incentive to reduce its production (and, in this way, to raise its nodal price). Accordingly, when the cheapgen holds all the available FTRs, the consumers located at node 1 benefit the most from the nodal price reduction while the surplus of the consumers located at node 2 remains at the benchmark's level (because the deargen has no extra incentive to reduce its production and, thus, increase its nodal price when $\alpha=1$). Consequently, the value of α that maximizes both consumer surplus and social welfare is $\alpha=1$, as it is evident in Fig. 4.[23]

[23] When $\alpha=1$ and $K=50$ MW, we obtain a Nash equilibrium characterized by: $q_1=550$ MWh, $q_2=225$ MWh, $P_1=\$50$/MWh, and $P_2=\$65$/MWh. In this case, social welfare is $W=PS+CS=\pi_1+\pi_2+CS_1+CS_2=\$28{,}250/\text{h}+\$10{,}125/\text{h}+\$12{,}500/\text{h}+\$7563/\text{h}=\$58{,}438/\text{h}$ (without considering any investment cost). This social welfare represents an increase of 3.4% with respect to the case without FTRs.

Fig. 4 shows the evolution of several equilibrium quantities, as α increases, when $K=50$ MW. In Fig. 4, $\Delta\pi_1^*$ corresponds to the change in the equilibrium cheapgen's profit due to an incremental transmission expansion from 50 MW to 52 MW; $\Delta\pi_2^*$ is the change in the equilibrium deargen's profit due to an incremental transmission expansion from 50 MW to 52 MW; CS^* is the equilibrium total consumer surplus ($K=50$ MW); and W^* represents the equilibrium social welfare ($K=50$ MW). In this figure, we verify both that $\Delta\pi_1^*$ is increasing in α, as Proposition 4 states, and that $\Delta\pi_2^*$ is decreasing in α, as stated in Proposition 7.

Using a procedure similar to the one followed in the benchmark case, we can compute the largest line capacity that can support a P/A Nash equilibrium, K', for different values of α. This is illustrated in Fig. 5. As Fig. 5 suggests, K' increases as α increases. For instance, with $\alpha=0.8$, we obtain $K'=90$ MW and, with $\alpha=0.5$, we obtain $K'=88$ MW. Consequently, as more FTRs are allocated to the cheapgen, both generation firms will support a P/A Nash equilibrium up to a larger transmission line capacity.

5. Conclusions

In this paper, we analyzed how the exercise of local market power by generation firms alters the firms' incentives to support incremental social-welfare-improving transmission investments in the context of a two-node network. We explored how such incentives are affected by the ownership structure of FTRs and how the FTRs' allocation may be used to align the incentives for transmission expansion of the society and of the net exporter generation firms.

Our analysis showed that, in the two-node network described, the net exporter generation firm (i.e., the cheapgen) has positive incentives to support an increase in the transmission capacity up to any level so that a passive/aggressive Nash equilibrium is still supported. We also proved that the change in the equilibrium cheapgen's profit due to an incremental transmission expansion will likely be increasing in the amount of FTRs that are allocated to the cheapgen. Moreover, we showed that, if all FTRs were allocated or auctioned off to the net exporter generation firm, then it is possible to increase both consumer surplus and social welfare while keeping the net exporter generation firm revenue neutral.[24]

We also showed that, although allocating FTRs to the net exporter generation firm can increase its incentives to support a social-welfare-improving transmission expansion, such a policy would dilute the net-importer-generation-firm's incentives to support the capacity expansion. Consequently, a socially concerned regulator who wants to align the incentives for transmission expansion of the society and of the net exporter firm must be aware that allocating FTRs to the net exporter firm would also increase the opposition of the net importer firm to support the expansion.

We conjecture that the results obtained in our analysis may generalize to more complex networks, but that has to be determined by future work, which will probably need to consider the case where the line capacity is neither too small nor too high (i.e., using the paper's notation, the case where K is such that $Min\{K',K^*\}<K<Max\{K',K^*\}$).

Finally, it is interesting to mention that one of the goals of market design and economic theory is to replace transitional administrative fixes, such as offer mitigation and capacity mechanisms, with structural means that align the participants' incentives so as to produce the socially desired outcomes. This paper is written with that objective in mind. Hence it is out of the scope of this paper to account for the fact that in some markets potential exercise of market power, which we try to deal with, can be suppressed through direct intervention by market monitors or through regulatory fiat.

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[24] Our conclusions are based on the static model proposed in this article. However, we recognize that transmission investments usually affect multiple time periods, in which generators have different cost structures and face different demands. If a firm's incentives change from hour to hour, we should consider how they add up to an overall willingness to support an incremental long-term social-welfare-improving transmission expansion. To overcome this intertemporal issue, we can work with average-over-time measures among different scenarios. An implementation of such an approach can be found in Sauma and Oren (2006). Specifically, we can build different scenarios of both demand and cost structures (which could happen in any hour of the year) and assign probabilities to the likelihood (or frequency of occurrence during the year) of each hourly scenario. Then, we can compute the equilibrium quantities in each scenario and take expectation over the scenarios, i.e., over time (note that this approach is different than considering the equilibrium quantities corresponding to an average scenario). Thus, the cheapgen will have incentives to support the incremental transmission expansion if, in expectation, its profit increases when holding FTRs.