# Aligning Generators' Interests with Social Efficiency Criteria for Transmission Upgrades in an LMP Based Market

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***Abstract*—In this paper, we present a numerical example to illustrate some situations under which generation companies in Locational Marginal Pricing (LMP) based markets could have the right incentives to support social-welfare-increasing network expansions. In particular, this paper focuses on the incentives that generation firms at generation pockets have to support transmission expansions and how these incentives are affected by the ownership of financial transmission rights (FTRs). We analyze the effect of local market power on such incentives when considering both that generation firms can hold FTRs and that generation firms cannot hold FTRs.**

***Index Terms*—Market power, network expansion planning, power system economics, transmission investment incentives.**

## I. INTRODUCTION

In this article, we present a numerical example to illustrate some situations under which generation companies in Locational Marginal Pricing (LMP) based markets could have the right incentives to support social-welfare-increasing network expansions. In particular, this paper focuses on the incentives that generation firms at generation pockets have to support 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 both that generation firms can hold FTRs and that generation firms cannot hold FTRs.

Some authors have proposed models that use different market mechanisms to improve the incentives for investing in the transmission sector. In [1], [2], [3], and [4], 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. In [5], the authors 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 this paper, 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.

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## II. THE NUMERICAL EXAMPLE

### A. General Framework

As a general framework for the analysis presented in this article, we assume that the transmission system uses locational marginal pricing, generation firms behave as Cournot oligopolists, thermal transmission line capacities are static and deterministic, 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.

We also assume 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.

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 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 firms' marginal costs of generation are constant and equal to zero for the generation firm located at node 1 (cheapgen) and \$20/MWh for the generation firm located at node 2 (deargen).

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 and downward sloping. In particular, we suppose that the inverse demand functions are $P_1(q) = 100 - 0.1 \cdot q$ at node 1 and $P_2(q) = 120 - 0.2 \cdot q$ at node 2, in \$/MWh.

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, this quantity ($q_t$) 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.

### B. *Scenario I: generation firms cannot hold FTRs.*

When generation firms cannot hold transmission rights, showing that generation firms with local market power can have disincentives to support socially beneficial investments in the transmission system could seem relatively simple. That is because we could argue that, by congesting the system, generation firms have the ability to exercise their local market power and deliberately withhold their outputs (or equivalently, increase their nodal prices) 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.

In [5], the authors use a two-node network similar to the one used in this article. They showed that, as the thermal capacity of the transmission line, K, increases from zero, one of two possible outcomes is obtained: [1]

Case 1:

- $0 < K < K'$: a passive/aggressive (P/A) Nash equilibrium exists,
- $K' < K < K^*$: no pure-strategy Nash equilibrium exists,
- $K^* < K$: an unconstrained Nash-Cournot equilibrium exists,

or

Case 2:

- $0 < K < K^*$: a P/A Nash equilibrium exists,
- $K^* < K < K'$: both P/A and unconstrained Cournot Nash equilibria exists,
- $K' < K$: an unconstrained Nash-Cournot equilibrium exists,

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 cheapgen to the deargen) and K* represents the smallest transmission line capacity that can support an unconstrained Nash-Cournot duopoly equilibrium (i.e., a Nash-Cournot duopoly equilibrium in which K is high enough so that the line is never congested).

Accordingly, if the transmission line capacity is high enough (i.e., $K > \mathrm{Max}\{K', K^*\}$), 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 the 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. Thus, with such a high-capacity line, the cheapgen would earn a profit of \$26,741/h and the deargen would earn a profit of \$7,407/h. Under these conditions, and without considering any investment cost, social welfare would be \$65,963/h.

The smallest transmission line capacity that can support an unconstrained Nash-Cournot duopoly equilibrium, K*, is approximately equal to 115 MW in this numerical example. We computed K* as follows.

The deargen's profit, when a line of capacity K is congested into its market, is $\pi_2(q_2^c) = q_2^c \cdot P_2(q_2^c+K) - C_2(q_2^c) = q_2^c \cdot [120 - 0.2 \cdot (q_2^c+K)] - 20 \cdot q_2^c = (100 - 0.2 \cdot K) \cdot q_2^c - 0.2 \cdot (q_2^c)^2$, 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 $\pi_2(q_2^{UCDE}) = \pi_2(q_2^{c*})$, or equivalently, $7{,}407 = 0.05 \cdot (500 - K^*)^2$. Thus, $K^* = 500 - \sqrt{(7{,}407 / 0.05)} \approx 115$ MW.

With $K = K^*$ ($\approx$ 115 MW), 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

[1] See Theorem 5 in [5].

Cournot best response to the cheapgen producing its unconstrained 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 congest 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 unconstrained 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. The situation described in this paragraph will occur for any line capacity between K' and K*.

On the other hand, if the transmission line capacity is low enough (i.e., K < Min{K', K*}), then generation firms maximize their profits by acting according to a Nash equilibrium in which the transmission line is congested with net flow from the cheapgen to the deargen (i.e., a P/A Nash equilibrium). 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. The largest line capacity that can support a P/A Nash equilibrium, K', is approximately equal to 53.6 MW in this numerical example. To compute K', we proceed as follows.

The cheapgen's profit, when a line of capacity K is congested from its market, is $\pi_1(q_1^c) = q_1^c \cdot P_1(q_1^c - K) - C_1(q_1^c) = q_1^c \cdot [100 - 0.1 \cdot (q_1^c - K)] - 0 = (100 + 0.1 \cdot K) \cdot q_1^c - 0.1 \cdot (q_1^c)^2$, 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 $q_2^{c(BR)}$ satisfying: $q_2^{c(BR)} = \text{Argmax}_{\{q_2\}} \bar{\pi}_2(q_2)$, where $\bar{\pi}_2(q_2) = q_2 \cdot P(q_1^{c*} + q_2) - C_2(q_2) = q_2 \cdot [106.67 - 0.067 \cdot (q_1^{c*} + q_2)] - 20 \cdot q_2 = (53.3 - 0.033 \cdot K) \cdot q_2 - 0.067 \cdot (q_2)^2$. The first-order optimality condition implies that $q_2^{c(BR)} = 0.25 \cdot (1600 - K)$. Thus, the deargen's profit from producing the Cournot best response to $q_1^{c*}$ is $\bar{\pi}_2(q_2^{c(BR)}) = (53.3 - 0.033 \cdot K) \cdot q_2^{c(BR)} - 0.067 \cdot (q_2^{c(BR)})^2 = (1600 - K)^2 / 240$. 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 $\bar{\pi}_2(q_2^{c(BR)}) = \pi_2(q_2^{c*})$. 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: $(1600 - K')^2 / 240 = 0.05 \cdot (500 - K')^2$. Thus, we have

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

With K = K' (≈ 53.6 MW), 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 transmission line of thermal 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 thermal capacity between 53.6 MW and 115 MW (i.e., K' < K < K*), no pure-strategy Nash equilibrium exists; and for a line of thermal capacity higher than 115 MW (i.e., K* < K), the unconstrained Nash-Cournot equilibrium characterized by $q_1^{UCDE} = 633$ MWh and $q_2^{UCDE} = 333$ MWh exists and is the unique pure-strategy Nash equilibrium.

Suppose that the capacity of the transmission line connecting the cheapgen and the deargen is currently 50 MW. With this transmission capacity, the cheapgen hourly produces 525 MWh of output while the deargen hourly generates 225 MWh and the market-clearing prices are $52.5/MWh at node 1 and $65/MWh at node 2, at the unique pure-strategy Nash equilibrium. Thus, at the unique equilibrium, the cheapgen earns a profit of $27,563/h and the deargen earns a profit of $10,125/h. Under these conditions, and without considering any investment cost, social welfare is equal to $56,531/h.

If the capacity of the transmission line were increased by a large-enough amount such that it became greater than K* (i.e., if the current line capacity were increased by more than 65 MW), 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, as previously mentioned. This would result in a reduction in profits for both generation firms as compared to the pre-expansion situation. Consequently, neither the cheapgen nor the deargen have incentive to support such an investment, although it improves 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 cheapgen would hourly produce 526 MWh while the deargen would hourly produce 224 MWh and the market prices would be $52.6/MWh at node 1 and \$64.8/MWh at node 2, at the unique pure-strategy Nash equilibrium. Thus, the cheapgen would earn a profit of \$27,668/h and the deargen would earn a profit of \$10,035/h. Under these conditions, and without considering any investment cost, social welfare would be \$56,554/h. 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, (ii) the equilibrium price at node 1 increases, (iii) the cheapgen's profit increases, (iv) the deargen reduces its output at the equilibrium, (v) the equilibrium price at node 2 decreases, (vi) the deargen's profit decreases, 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. However, this conclusion is only valid for upgrades that increase the capacity of the line up to K'. This means that if, as we assumed, the current line capacity is 50 MW, then the "positive" incentives of the cheapgen to support socially-efficient transmission investments are only guaranteed for incremental expansions smaller than 3.6 MW.

### C. *Scenario II: generation firms can hold some FTRs.*

Assume now that generation firms can hold some FTRs. In particular, suppose that the cheapgen and the deargen hold fractions $\alpha_1$ and $\alpha_2$ of the K FTRs available from node 1 to node 2, respectively. These fractions must satisfy $\alpha_1 + \alpha_2 \leq 1$, where $\alpha_1$ and $\alpha_2 \in [0,1]$.

If the transmission line capacity were high enough (i.e., K > Max{K', K*}) 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).

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.

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. 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.

On the other hand, when the P/A Nash equilibrium is supported, the deargen maximizes its profit as if it had monopoly power over its K-leftward-shifted inverse demand function, but having two revenues streams now: a first stream of revenue from energy sales and a second revenue stream from the congestion rents. Accordingly, 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.

The previous analysis leads to the conclusion that as the cheapgen holds more FTRs, the consumers located at node 1 benefit more from the resulting nodal price reduction. This fact could justify the allocation of all FTRs to net exporter generation firms (the cheapgen, in our example) because this could increase social welfare.

Now, suppose that each firm holds half of the available FTRs (i.e., $\alpha_1 = \alpha_2 = 0.5$). In this case, assuming that the current line capacity is 50 MW, the cheapgen hourly produces 537.5 MWh while the deargen hourly generates 212.5 MWh and the market-clearing prices are \$51.3/MWh at node 1 and \$67.5/MWh at node 2, at the unique Nash equilibrium. Thus, with these FTRs fractions, the cheapgen earns a profit of \$27,953/h and the deargen earns a profit of \$10,500/h. (Under these conditions, and without considering any investment cost, social welfare is \$57,227/h.) Consequently, this numerical example makes clear that, by holding some FTRs, both generation firms increase their profits with respect to the benchmark case. Furthermore, by comparing the benchmark case and the case where $\alpha_1 = \alpha_2 = 0.5$, we conclude 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.

With a procedure similar to the one used in the benchmark case, we can compute both K* and K' for different values of $\alpha_1$ and $\alpha_2$. By varying $\alpha_1$ and $\alpha_2$, it is easy to verify that both K* and K' increase as $\alpha_1$ and/or $\alpha_2$ increase. For instance, with $\alpha_1 = \alpha_2 = 0.5$, we obtain K* = 127.3 MW and K' = 88 MW, which confirms an increase in the values of K' and K* with respect to the benchmark case. Consequently, in this case, both generation firms will support a P/A Nash equilibrium up to a line capacity larger than the benchmark case threshold. This result suggests that, while the P/A Nash equilibrium prevails, it would be more likely that the cheapgen supports a social-welfare-improving transmission expansion when it holds FTRs than when it does not hold FTRs.

## III. Conclusions

In this paper, we present a numerical example to illustrate some situations under which generation companies in LMP based markets could have the right incentives to support social-welfare-increasing network expansions. In particular, we analyzed how the exercise of local market power by generation firms alters the firms' incentives to support 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 network expansion of the different market participants.

Our analysis of showed that, as long as 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. We also showed that, when the generation firms hold FTRs, these firms will support a P/A Nash equilibrium up to a line capacity larger than the benchmark case threshold, which implies that it is more likely that the cheapgen supports a social-welfare-improving transmission expansion when it holds FTRs than when it does not hold FTRs.

We also showed that, by holding some FTRs, both generation firms could increase their profits with respect to the benchmark case. Furthermore, we showed that if all FTRs were allocated to generation firms that are net exporters, then these firms would have the correct incentives to support social-welfare-improving transmission expansions.

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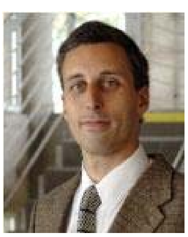


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