# Alternative Economic Criteria and Proactive Planning for Transmission Investment in Deregulated Power Systems

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**Abstract**

This paper explains why the maximization of social welfare can be insufficient to achieve Pareto efficiency in deregulated electric systems. Furthermore, we illustrate, through a simple example, how different optimizing objectives can result in divergent optimal expansion plans of a transmission network. This fact carries some important policy implications, one of which is that merchant investment must be carefully scrutinized since it may disadvantage some constituents and preempt future superior investment plans. This paper also suggests the introduction of a three-period model of transmission investments as a new planning paradigm that takes into consideration the policy implications of the conflicting incentives for transmission investment and explicitly considers the interrelationship between generation and transmission investments in power systems.

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## 1. INTRODUCTION

Transmission investment in vertically integrated power industries where traditionally motivated by reliability considerations as well as the economic objective of connecting load areas to remote cheap generation resources. This was done within the framework of an integrated resource planning paradigm so as to minimize investment in transmission generation and energy cost while meeting forecasted demand and reliability criteria. The cost of such investments, once approved by the regulator, plus an adequate return on investment, has been incorporated into customers' rate base. Vertical unbundling of the electricity industry and the reliance on market mechanisms for pricing and return on investments have increased the burden of economic justification for investment in the electricity infrastructure. The role of regional assessment of transmission expansion needs and approval of proposed projects has shifted in many places from the integrated utility to a regional transmission organization (RTO) which is under the jurisdiction of the Federal Energy Regulatory Commission (FERC) while the funding of such projects through the regulated rates is still under the jurisdiction of state regulators.

In evaluating the economic implications of transmission expansions the RTO and state regulators must take into considerations that in a market based system such expansions may create winners and losers, even when the project as a whole is socially justifiable on the grounds of reliability improvements and energy cost savings. Furthermore, in the new environment, transmission expansion may be also justified as a mean for facilitating free trade and as a market mitigation approach to reducing locational market power.

From an economic theory perspective, the proper criterion for investment in the transmission infrastructure is the maximization of social welfare which is composed of consumers' and producers' surplus which also accounts for investment cost and may account for reliability by including the social cost of unreliability in this objective function. When demand is treated as inelastic social welfare maximization is equivalent to total cost minimization including energy cost investment cost and cost of lost load or other measure of unreliability cost. The validity of this economic objective is premised on the availability of *adequate and costless* (without transaction costs) transfer mechanisms among market participants which assures that increases in social welfare will result in Pareto improvements (making all participants better off or neutral).

However, this principle is not always true in deregulated electric systems, where transfers are not always feasible and even when attempted are subject to many imperfections. In the U.S. electric system, which was originally designed to serve a vertically integrated market, there are misalignments between payments and rewards associated with use and investments in transmission. In fact, while payments for transmission investments and for its use are made locally (at state level), the economic impacts from these transmission investments extend beyond state boundaries so that the planning and approval process for such investment falls under FERC jurisdiction. As a result of such jurisdictional conflict side adequate payments among market participants are not always physically or politically feasible (for instance, this would be the case of a network expansion that benefit a particular generator or load in another state, so that the cost of the expansion is not paid for by those who truly benefit from it).[1] Consequently, the maximization of social welfare may not translate to Pareto efficiency and other optimizing objectives should be considered. Unfortunately, alternative objectives may produce conflicting results with regard to the desirability of transmission investments.

One potential solution to the aforementioned jurisdictional conflict is the so-called "participant funding", which was proposed by FERC in its 2002 Notice of Proposed Rulemaking (NOPR) on Standard Market Design (FERC 2002, 98-115). Roughly, participant funding is a mechanism whereby one or more parties seeking the expansion of a transmission network (who will economically benefit from its use) assume funding responsibility. This scheme would assign the cost of a network expansion to the beneficiaries from the expansion thus, eliminating (or, at least, mitigating) the side-payments' problem mentioned above. This policy is based on the rationale that, although most network expansions are used by and benefit all users, some few network

[1] For example, it is really hard to convince people in Idaho that they should pay for a transmission line connecting Idaho and California to carry their cheap power to Californians. On the contrary, they would probably be worry about both a likely increase in their electricity prices and a potential reduction in the reliability of their own system because of the increased risk of cascading failures (due to the expansion).

expansions will only benefit an identifiable customer or group of customers (such as a generator building to export power or a load building to reduce congestion).

Although participant funding would potentially encourage greater regional cooperation to get needed facilities sited and built, this approach has some caveats in practice. The main shortcomings of participant funding are:

- The benefits from network upgrades are difficult to quantify and to allocate among market participants (and, thus, it could be difficult to identify and avoid detrimental expansions that benefit some participants, either at the expense of others or decreasing social welfare).
- Mitigation of network bottlenecks is likely to require a program of system-wide upgrades, from which almost all market participants are likely to benefit, but for which the cumulative benefits can be difficult to capture through participant funding.
- After some period of time (but less than the economic life of the upgrade), if the benefits begin to accrue to a broader group of customers, then some form of crediting mechanism should be established to reimburse the original funding participants. However, this would basically be a reallocation of sunk costs.
- Participant funding could lead to a sort of "incremental expansions" over time. Because transmission investments tend to be lumpy, these incremental expansions may be inefficient in the long run and more costly to consumers.
- Providing some form of physical (capacity-reservation) rights in exchange for participant-funded investments could allow the exercise of market power by the withholding of the new capacity and, thereby, create new transmission bottlenecks.
- An extensive reliance on participant funding and incentive rates for transmission could lead to accelerated depreciation lives for ratemaking purposes, which will increase the risk profile for this portion of the industry.

Most of the works found in the literature about transmission planning in deregulated electric systems consider single-objective optimization problems (maximization-of-social-welfare in most of the cases) while literature that considers multiple optimizing objectives is scarce. London Economics International LLC (2002) developed a methodology to evaluate specific transmission proposals using an objective function for transmission appraisal that allows the user to vary the weights applied to producer and consumer surpluses. However, London Economics' study has no view on what might constitute appropriate weights nor on how changes in the weights affect the proposed methodology. Sun and Yu (2000) propose a "multiple-objective" optimization model for transmission expansion decisions in a competitive environment. To solve this model, however, the authors convert it into a single-objective optimization model by using fuzzy set theory. Styczynski (1999) uses a multiple-objective optimization algorithm to clarify some issues related to the transmission planning in a deregulated environment. The fact that most of this work is directly applied to the European distribution expansion problem, which is nearly optimally solved, makes uncertain the real value of this model in practice. Shrestha and Fonseka (2004) utilize a trade off between the change in the congestion cost and the investment cost associated with a transmission expansion in order to determine the optimal expansion decision. Unfortunately, this work is not very useful in practice because of some excessively simplistic assumptions made in their decision model (e.g., ignoring the exercise of market power by generation firms).

Although some authors have used multiple optimizing objectives for transmission planning, none of them has analyzed the conflicts among these different objectives and their policy implications. This chapter attempts to show that different desired optimizing objectives can result in divergent optimal expansions of a transmission network and that this fact entails some very important policy implications, which should be considered by any decision maker concerned with transmission expansion.

The rest of the chapter is organized as follows. In section 2, we present a simple radial-network example that illustrates how different optimizing objectives can result in divergent optimal expansion plans of a network. Section 3 explains the policy implications of the conflicts among these different optimizing objectives. In section 4, we suggest a three-period model of transmission investments to evaluate transmission expansion projects. This model takes into account the policy implications of the conflicting incentives for transmission investment and explicitly considers the interrelationship between generation and transmission investments in oligopolistic power systems. In section 5, we illustrate the results of our three-period model with a numerical example. Section 6 concludes the chapter and describes future work.

## 2. CONFLICTING OPTIMIZATION OBJECTIVES FOR NETWORK EXPANSIONS

### 2.1 A Radial-Network Example

For any given network, the network planner would ideally like to find and implement the transmission expansion that maximizes social welfare, minimizes the local market power of the agents participating in the system, maximizes consumer surplus and maximizes producer surplus. Unfortunately, these objectives may produce conflicting results with regard to the desirability of various transmission expansion plans. In this section, we illustrate, through a simple example, the divergent optimal transmission expansions based on different objective functions, and the difficulty of finding a unique network expansion policy.

We shall use a simple two-node network example as shown in Figure 1 which is sufficient to highlight the potential incompatibilities among the planning objectives and their policy implications. This example is chosen for simplicity reasons and does not necessarily represent the behavior of a real system.

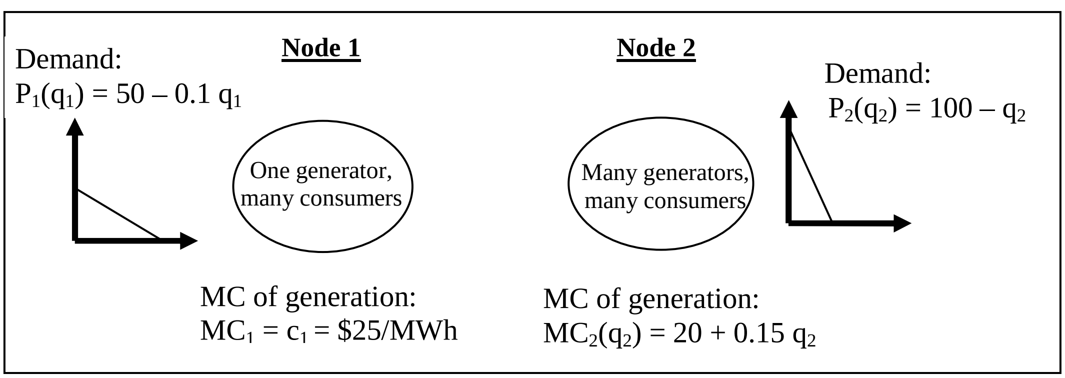


Figure 1: An illustrative two-node example

As a general framework of the example presented here, we assume that the transmission system uses nodal pricing, transmission losses are negligible, consumer surplus is the correct measure of consumer welfare (e.g., consumers have quasi-linear utility), generators cannot purchase transmission rights (and, thus, their bidding strategy is independent of the congestion rent), and the Lerner index (defined as the fractional price markup, i.e. [price – marginal cost] / price) is the proper measure of local market power.

Consider a network composed of two unconnected nodes where electricity demand is served by local generators. Assume node 1 is served by a monopoly producer, while node 2 is served by a competitive fringe.[2] For simplicity, suppose that the generation capacity at each node is unlimited. We also assume both that the marginal cost of generation at node 1 is constant (this is not a critical assumption, but it simplify the calculations) and equal to $c_1$ = \$ 25/MWh, and that the marginal cost of generation at node 2 is linear in quantity and given by $MC_2(q_2) = 20 + 0.15 \cdot q_2$. Moreover, we assume linear demand functions. In particular, the demand for electricity at node 1 is given by $P_1(q_1) = 50 - 0.1 \cdot q_1$ while the demand for electricity at node 2 is given by $P_2(q_2) = 100 - q_2$.

We analyze the optimal expansion of the described network under each of the following optimizing objectives: (1) maximization of social welfare, (2) minimization of local market power, (3) maximization of consumer surplus, and (4) maximization of producer surplus. [3] We limit the analysis to only two possible network expansion options: i) doing nothing (that is, keeping each node as self-sufficient) and ii) building a transmission line with "adequate" capacity (that is, building a line with high-enough capacity so that the probability of congestion is very small). For the particular cases we present here, we can easily verify that the optimal expansion under each of

[2] The fact that the generation firm located at node 1 can exercise local market power is a crucial assumption for the purpose of this example. Without considering local market power, the results we show in this section are no longer valid. However, this supposition is fairly realistic. In fact, perfectly competitive markets are not very common in the power generation business. In our example, the perfect-competition assumption at node 2 is only made for simplicity and it can be eliminated without changing any of the qualitative results presented in this section.

[3] In this section, we show that, for given demand functions, the optimal expansions under the four considered optimizing objectives vary depending on the cost structures of generators. To do this, we analyze the optimal expansion of the two-node network when changing the marginal cost of generation at node 1 (i.e., when we change $c_1$) while keeping unaltered the cost structure of the generators at node 2.

the four considered optimizing objectives is truly either doing nothing or building a transmission line with adequate capacity. In the general case, we can justify this simplification based on the lumpiness of transmission investments.

Under the scenario in which each node satisfy its demand for electricity with local generators (self-sufficient-node scenario), the generation firm located at node 1 behaves as a monopolist (that is, it chooses a quantity such that its marginal cost of supply equals its marginal revenue) while the generation firms located at node 2 behave as competitive firms (that is, they take the electricity price as given by the market-clearing rule: demand equals marginal cost of supply).

Accordingly, under the self-sufficient-node scenario (SSNS), the generation firm at node 1 optimally produces $q_1^{(SSNS)}$ = 125 MWh and charges $P_1^{(SSNS)}$ = \$37.5 /MWh. With this electricity quantity and price, the producer surplus at node 1 (which, in this example, is equivalent to the monopolist's profit) is $PS_1^{(SSNS)}$ = \$ 1,563 /h and the consumer surplus at this node equals $CS_1^{(SSNS)}$ = \$781 /h. The Lerner index at node 1 is $L_1^{(SSNS)}$ = 0.33.[4] On the other hand, under the SSNS, the generation firms located at node 2 optimally produce an aggregate amount equal to $q_2^{(SSNS)}$ = 69.6 MWh, and the market-clearing price is $P_2^{(SSNS)}$ = \$30.4 /MWh. With this electricity quantity and price, the producer surplus at node 2 is $PS_2^{(SSNS)}$ = \$ 363 /h and the consumer surplus at this node is $CS_2^{(SSNS)}$ = \$2,420 /h. [5] From the previous results, we can compute the total producer surplus, the total consumer surplus, and the social welfare under the SSNS. The numerical results are given by: $PS^{(SSNS)} = PS_1^{(SSNS)} + PS_2^{(SSNS)}$ = \$1,926 /h; $CS^{(SSNS)} = CS_1^{(SSNS)} + CS_2^{(SSNS)}$ = \$3,201 /h; and $W^{(SSNS)} = PS^{(SSNS)} + CS^{(SSNS)}$ = \$5,127 /h; respectively.

[4] Under monopoly, if the marginal cost of production is constant and equal to c and the demand is linear, given by $P(q) = a – b·q$, 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 $CS^{(M)} = (a – c)^2 / (8b)$, and the Lerner index at the monopolist's node is equal to $L^{(M)} = (P^{(M)} - c) / P^{(M)} = (a – c) / (a + c)$.

[5] Under perfect competition, if the marginal cost of supply is linear, given by $MC(q) = c + d·q$, and the inverse demand function is given by $P(q) = a – b·q$, where $a > c$, then the market will optimally produce a quantity $q^{(PC)} = (a–c) / (b + d)$ and the market-clearing price will be $P^{(PC)} = (a·d + b·c) / (b + d)$. Under these assumptions, the producer surplus is equal to $PS^{(PC)} = (d·(a – c)^2) / (2·(b + d)^2)$ and the consumer surplus is $CS^{(PC)} = (b·(a – c)^2) / (2·(b + d)^2)$.

Now, we consider the scenario in which there is adequate (ideally unlimited) transmission capacity between the two nodes (adequate-transmission-capacity scenario). Under this scenario, the generation firms face an aggregate demand given by:

$$P(Q) = \begin{cases} 100 - Q & , \text{if } Q < 50 \\ 54.5 - 0.09 \cdot Q & , \text{if } Q \geq 50 \end{cases} ,$$

where Q is the total amount of electricity produced. That is, $Q = q_1 + q_2$, where $q_1$ is the amount of electricity produced by the firm located at node 1 and $q_2$ is the aggregate amount of electricity produced by the firms located at node 2.

Under the adequate-transmission-capacity scenario (ATCS), the two nodes may be treated as a single market where the generator at node 1 and the competitive fringe at node 2 jointly serve the aggregate demand of both nodes at a single market clearing price. We assume that the monopolist at node 1 behaves as a Cournot oligopolist interacting with the competitive fringe. That is, under the ATCS, we assume both that the monopolist at node 1 chooses a quantity such that its marginal cost of supply equals its marginal revenue, taking the output levels of the other generation firms as fixed, and that the generation firms at node 2 still take the electricity price as given by the market-clearing rule.

Thus, according to the Cournot assumption, under the ATCS, the monopolist at node 1 optimally produces $q_1^{(ATCS)}$ = 112 MWh while the competitive fringe at node 2 optimally produces $q_2^{(ATCS)}$ = 101.2 MWh (these output levels imply that there is a net transmission flow of 36 MWh from node 2 to node 1). In this case, the market-clearing price (which is the price charged by all firms to consumers) is $P^{(ATCS)}$ = \$35.2 /MWh. With these new electricity quantities and prices, the producer surplus at node 1 is equal to $PS_1^{(ATCS)}$ = \$ 1,139 /h and the producer surplus at node 2 is equal to $PS_2^{(ATCS)}$ = \$ 768 /h.[6] As well, the consumer surpluses are $CS_1^{(ATCS)}$ = \$1,099 /h for node 1's

[6] Under the ATCS, assuming generators behave as Cournot firms, if the marginal costs of supply at nodes 1 and 2 are $MC_1(q_1) = c_1$ and $MC_2(q_2) = c_2 + d_2 \cdot q_2$ respectively, and the aggregate demand is linear, given by $P(Q) = A - B \cdot Q$, where $A > c_1$ and $A > c_2$, then the optimal output levels solve the following two equations:

$$A - 2 \cdot B \cdot q_1 - B \cdot q_2 = c_1 \quad (\text{or } MR_1 = MC_1) \text{ and}$$
$$A - B \cdot (q_1 + q_2) = c_2 + d_2 \cdot q_2 \quad (\text{or } P^{(ATCS)} = MC_2)$$

consumers and $CS_2^{(ATCS)}$ = \$2,101 /h for node 2's consumers. The new Lerner index at node 1 is $L_1^{(ATCS)} = 0.29$.

From the above results, we can compute the total producer surplus, the total consumer surplus, and the social welfare under the ATCS. However, these calculations require knowing who is responsible for the transmission investment costs. Without loss of generality, we assume that an independent entity (other than the existing generation firms and consumers) incurs in the transmission investment costs. Consequently, under the ATCS, total producer surplus (not accounting for transmission investment cost) is $PS^{(ATCS)} = PS_1^{(ATCS)} + PS_2^{(ATCS)}$ = \$1,907 /h; total consumer surplus is $CS^{(ATCS)} = CS_1^{(ATCS)} + CS_2^{(ATCS)}$ = \$3,200 /h; and social welfare is $W^{(ATCS)} = PS^{(ATCS)} + CS^{(ATCS)}$ – investment costs = \$5,107 /h – investment costs.

Comparing both the SSNS and the ATCS, we can observe that the expansion that minimizes local market power is building a transmission line with "adequate" capacity (at least theoretically, with capacity greater than 36 MWh) since $L^{(ATCS)} < L^{(SSNS)}$. However, the expansion that maximizes social welfare would keep each node as self-sufficient ($W^{(ATCS)} < W^{(SSNS)}$ , even if the investment costs were negligible). Moreover, both the expansion that maximizes total consumer surplus and the expansion that maximizes total producer surplus are keeping each node as self-sufficient (i.e., $CS^{(ATCS)} < CS^{(SSNS)}$ and $PS^{(ATCS)} < PS^{(SSNS)}$ ). This means that, in this particular case, while the construction of an adequate-capacity transmission line linking both nodes minimizes the local market power of generation firms, this network expansion decreases social welfare, total consumer surplus, and total producer surplus. Figures 2, 3 and 4 illustrate these findings.

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The solution to this system of equations is: $q_1^{(ATCS)} = (B\cdot(c_2 - c_1) + d_2\cdot(A - c_1)) / (B\cdot(B + 2\cdot d_2))$ and $q_2^{(ATCS)} = (A - 2\cdot c_2 + c_1) / (B + 2\cdot d_2)$. Under these assumptions, the market-clearing price is $P^{(ATCS)} = ( d_2\cdot(A + c_1) + c_2\cdot B ) / (B + 2\cdot d_2)$. According to this market-clearing price and the optimal output levels, the producer surplus at node 1 is $PS_1^{(ATCS)} = (B\cdot(c_2-c_1) + d_2\cdot(A-c_1) )^2 / (B\cdot(B+2d_2)^2 )$, and the producer surplus at node 2 is $PS_2^{(ATCS)} = (d_2\cdot(A - 2\cdot c_2 + c_1 )^2) / (2\cdot(B + 2d_2 )^2)$.

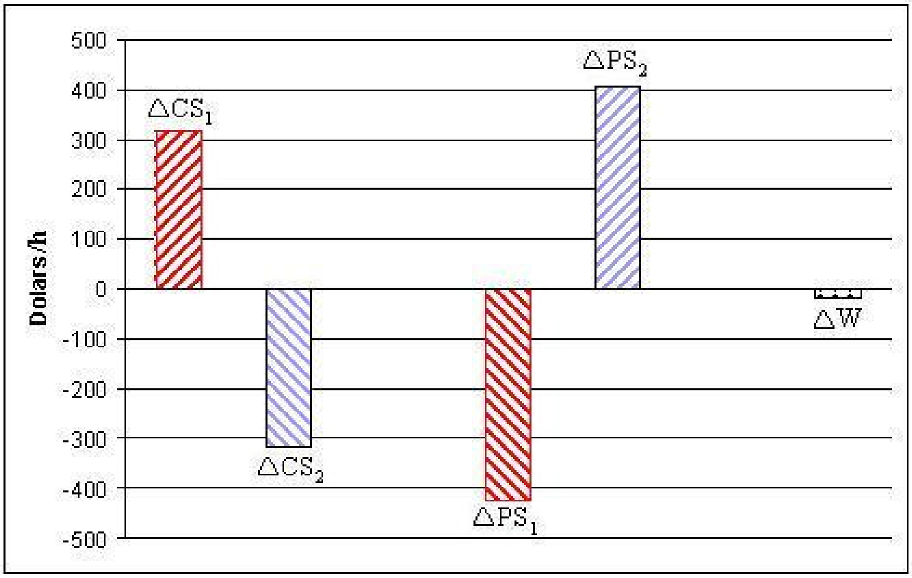


Figure 2: Effects on consumers and producers of building an adequate-capacity line between both nodes, assuming that the investment cost is negligible.

Figure 2 demonstrates that, in this particular case, the construction of the adequate-capacity transmission line reduces social welfare even if the investment costs were negligible. Furthermore, this figure leads to an interesting observation: if the consumers at node 1 (and/or the producers at node 2) had enough political power, then they could encourage the construction of an adequate-capacity transmission line linking both nodes even though it would decrease social welfare. That is, in this case, the “winners” from the transmission investment (consumers at node 1 and generation firms at node 2) can be expected to expend up to the amount of rents that they stand to win to obtain approval of this expansion project although it reduces social welfare.

It is interesting to note that, in this example, building the transmission line between the two nodes will result in flow from the expansive generation node to the cheap node so that the transmission line cannot realize the potential *gains from trade* between the two nodes. On the contrary such flow decreases social welfare due to the exporting of power from an expensive-generation area into a cheap-generation area. This phenomenon is due to the exercise of market power by the generator at node 1 who finds it advantageous to let the competitive fringe increase its production by exporting power to the cheap node in order to sustain a higher market price. In economic trade theory, *gains from trade* is defined as the improvement in consumer incomes and producer revenues that arise from the increased exchange of goods or services among the trading areas (countries in international trade studies). It is well understood that, in absence of local market power (e.g., excluding all monopoly rents), the trade between areas must increase the total utility of all the areas combined. That is, *gains from trade* must be a non-negative quantity (Sheffrin, 2005). This rationale underlines common wisdom that prevailed in a regulated environment justifying the construction of transmission between cheap and expansive generation node on the grounds of reducing energy cost to consumers. However, as our example demonstrates, such rationale may no longer hold in a market-based environment where market power is present. Moreover, if we excluded monopoly rents from our social welfare calculations, then we would obtain zero gain from trade, in agreement with the *gains from trade* economic principle. However, even in that case, our example would still help us to illustrate that transmission expansions have distributional impacts, which create conflicts of interests among market participants.

Figure 3 and Figure 4 assists us to explain the results obtained in our particular example. These two figures show the price-quantity equilibria at each node under the two considered scenarios. In these figures, the solid lines represent the equilibria under the SSNS while the dotted lines correspond to the equilibria under the ATCS.

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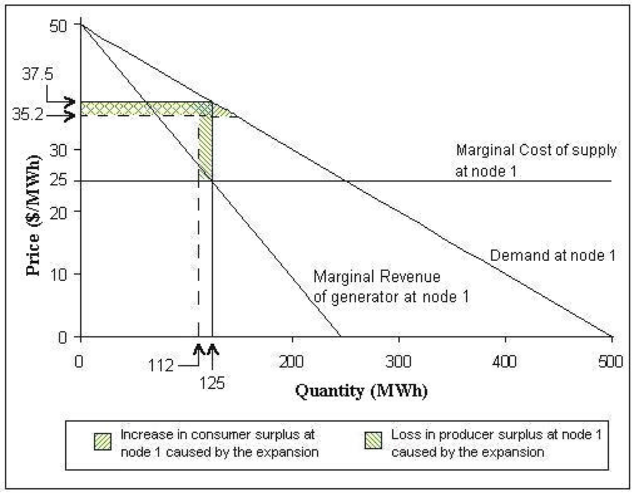


Figure 3: Equilibrium at node 1 under both the SSNS and the ATCS

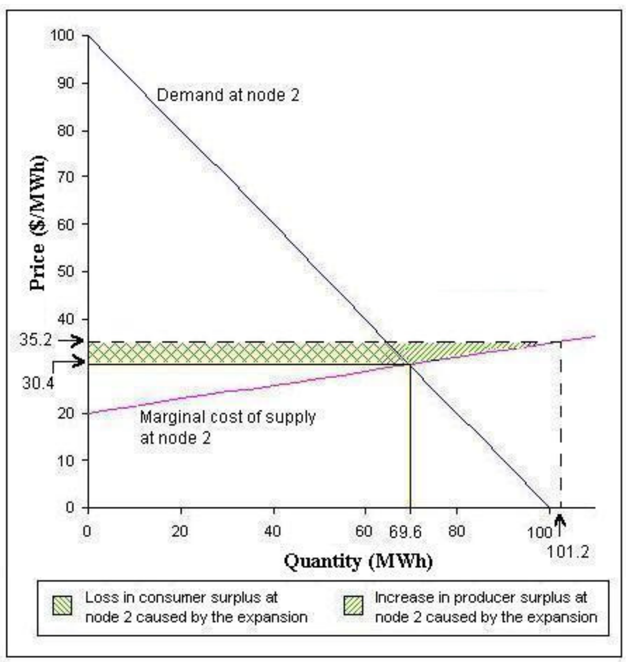


Figure 4: Equilibrium at node 2 under both the SSNS and the ATCS.

One way to explain the results obtained in the example presented in this section is through the distinction between two different effects due to the construction of the adequate-capacity transmission line, as suggested by Leautier (2001). On one hand, competition among generation firms increases. This effect "forces" the firm located at node 1 to decrease its retail price with respect to the SSNS. On the other hand, the transmission expansion causes a substitution (in production) of some low-cost power by more expensive power as result of the exercise of local market power.

The construction of the adequate-capacity transmission line allows market participants to sell/buy power demanded/produced far away. This characteristic encourages competition among generation firms. In our example, the introduction of competition entails a decrease in the retail price at node 1 with respect to the SSNS. As shown in Figure 3, this price reduction causes an increase in the node 1's consumer surplus (because the demand at node 1 increases) and a reduction in the profit of the monopolist at node 1 with respect to the SSNS.

Moreover, because of the ability to exercise local market power, the monopolist at node 1 can reduce its output (although the demand at node 1 increases with respect to the SSNS) and keep a retail price higher than the SSNS market-clearing price at node 2 in order to maximize its profit under the ATCS. As this happens, the node 2's firms increase their output levels (increasing both the generation marginal cost and the retail price at node 2 with respect to the SSNS equilibrium) up to the point in which the retail prices at both nodes are equal (assuming the transmission constraint is not binding) and the total demand is met, ATCS equilibrium. As shown in Figure 4, at this new equilibrium, the producer surplus at node 2 increases while the consumer surplus at node 2 decreases with respect to the SSNS. In other words, because the power generation at node 1 is cheaper than the one at node 2 for the relevant output levels, the exercise of local market power by the node 1's firm causes a substitution of some of the low-cost power generated at node 1 by more expensive power produced at node 2 to meet demand. This out-of-merit generation, caused by the transmission expansion, reduces social welfare with respect to the SSNS.

Summarizing, while the first effect (competition effect) is social-welfare improving, the second effect (substitution effect) is social-welfare decreasing in the case of the example presented in this section. Furthermore, the substitution effect dominates in this particular example. Two facts contribute to the explanation of the dominance of the substitution effect: i) the generation marginal cost at node 1 is much lower than the one at node 2 (for the relevant output levels), although the pre-expansion price at node 1 is higher than the equilibrium price at node 2, and ii) the demand and supply elasticities at node 2 are higher than those at node 1.

The analysis shown in this section makes evident that the transmission expansion plan that minimizes local market power of generation firms may differ from the expansion plan that maximizes social welfare, consumer surplus, or total producer surplus when the effect of the expansion on market prices is taken into consideration. Likewise the transmission expansion plan that maximizes total producer surplus may differ from the expansion plan that maximizes social welfare and consumer surplus while the transmission expansion plan that maximizes total consumer surplus may differ from the expansion plan that maximizes social welfare. These conclusions can all be drawn based on the simple two node example given above (see the Appendix for detailed calculations).

Finally, it is worth to mention that our Cournot assumption is not essential in order to derive the qualitative results and conclusions presented here. The different optimization objectives we have considered may result in divergent optimal transmission expansion plans even when we model the competitive interaction of the generation firms as Bertrand competition.

### 2.2 Sensitivity Analysis in the Radial-Network Example

It is interesting to study the behavior of our two-node network under perturbation of some supply and/or demand parameters. Next, we present a sensitivity analysis of the optimal network expansion decision with respect to the marginal cost of supply at node 1, $c_1$.

Figure 5 shows the changes in the optimal network expansion plan, under each of the four optimization objectives we have considered, as we vary the marginal cost of generation at node 1 (keeping all other parameters unaltered and assuming that investment costs are negligible).

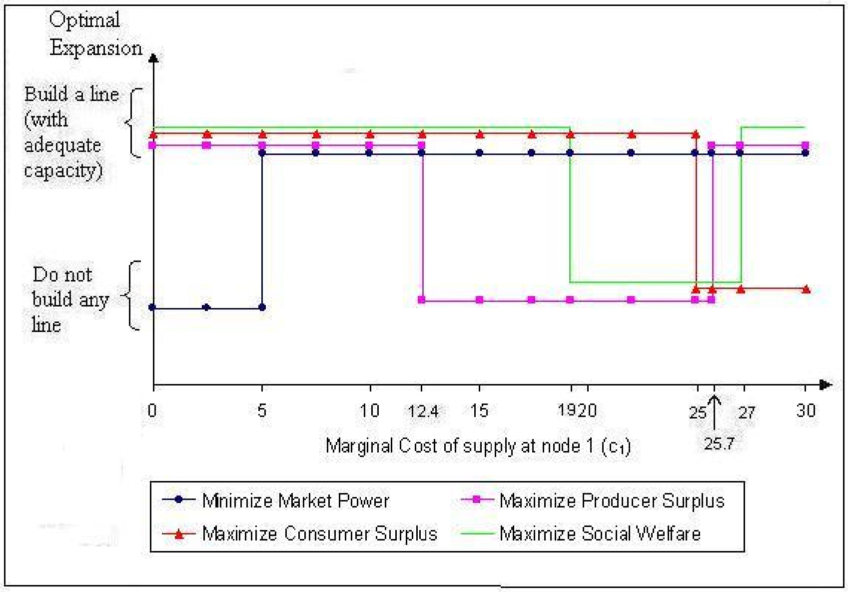


Figure 5: Sensitivity to the marginal cost of supply at node 1 in the two-node network.

We note that none of the optimizing objectives leads to a consistent optimal expansion for all values of the parameter $c_1$. Moreover, this figure demonstrates that only for values of $c_1$ between \$5 /MWh and \$12.4 /MWh the four optimization objectives lead to the same optimal expansion plan. For $c_1$ higher than \$5 /MWh, the competition among generation firms intensifies under the ATCS, forcing the monopolist at node 1 to reduce its retail price (i.e., $P_1^{(ATCS)} < P_1^{(SSNS)}$ ), thus decreasing the monopolist's local market power. Moreover, for $c_1$ lower than \$12.4 /MWh, under the SSNS, the monopolist at node 1 sets a retail price lower than the equilibrium price at node 2 (i.e., $P_1^{(SSNS)} < P_2^{(SSNS)}$ ). Thus, under the ATCS, there is a net transmission flow from node 1 to node 2 which improves producer surplus, consumer surplus, and social welfare with respect to the SSNS.

Another interesting observation from Figure 5 is that the optimal network expansion plan under most of the optimization objectives is highly sensitive to the marginal cost of generation at node 1 when this parameter has values between \$25 /MWh and \$27 /MWh.

We also performed a sensitivity analysis of the optimal network expansion plan with respect to some demand parameters. Modifying some of the demand function parameters, while keeping all supply parameters unaltered leads to qualitative results that are similar to those observed when we vary the supply cost at node 1. Such analysis shows that the optimal expansion plan under each of the four optimization objectives is highly sensitive to the demand structure.

## 3. POLICY IMPLICATIONS

The results discussed in the previous section have two important policy implications.

First, we observed that the optimal expansion of a network depends on the optimizing objective utilized and can be highly sensitive to supply and demand parameters. Even when the optimizing objective is clearly determined, the optimal network expansion plan changes depending on the cost structure of the generation firms. However, generation costs are typically uncertain and depend on factors like the available generation capacity or the generation technology used which in turn affect the optimal network investment plan. It follows that the interrelationship between generation and transmission investments should be considered when evaluating any transmission expansion project. Accounting for such interactions has been part of the integrated resource planning paradigm that prevailed under the regulated vertically integrated electricity industry but is no longer feasible in the restructured industry.  In section 4 below we describe a new planning paradigm that offers a way of accounting for generators response to transmission investment in an unbundled electricity industry with a competitive generation sector.

Second, our analysis shows that transmission investments have important distributional impact. While some transmission investments can greatly benefit some market participant, they may harm some other constituents. Consequently, policy makers looking after socially efficient network expansions should be aware of the distributional impact of merchant investments. Moreover, the dynamic nature of power systems entails changes over time of not only demand and supply structures, but also the mix of market participants, which adds complexity to the valuation of merchant transmission expansion projects. Even when a merchant investment appears to be beneficial under the current market structure, the investment could become socially inefficient when future generation and transmission plans and/or demand forecasts are considered.

## 4. PROACTIVE TRANSMISSION PLANNING

In this section we introduce a three-period model as a new planning paradigm that takes into consideration the policy implications reviewed in the previous section. The basic idea behind this model is that the interrelationship between the generation and the transmission investments affects the social value of the transmission capacity so that transmission planning must take into consideration its effect both on generation investment and on the resulting market equilibrium while recognizing that investment decisions in generation will respond to the transmission expansion plan, in anticipation of the subsequent market equilibrium conditions.

### 4.1 Model Assumptions

The model does not assume any particular network structure, so that it can be applied to any network topology. Moreover, we assume that all nodes are both demand nodes and generation nodes and that all generation capacity at a node is own by a single firm. We allow generation firms to exercise local market power and assume that their interaction can be characterized through Cournot competition, i.e., firms chose their production quantities so as to maximize their profit with respect to the residual demand function while taking the production quantities of other firms and the dispatch decisions of the system operator as given. Furthermore, the model allows many lines to be simultaneously congested as well as probabilistic contingencies describing demand shocks, generation outages and transmission line outages.

The model consists of three periods, as displayed in Figure 6. We assume that, at each period, players making decisions observe all previous-periods actions and form rational expectations regarding the outcome of the current and subsequent periods. That is, we define the transmission investment model as a "complete- and perfect-information" game[7] and the equilibrium as "sub game perfect".

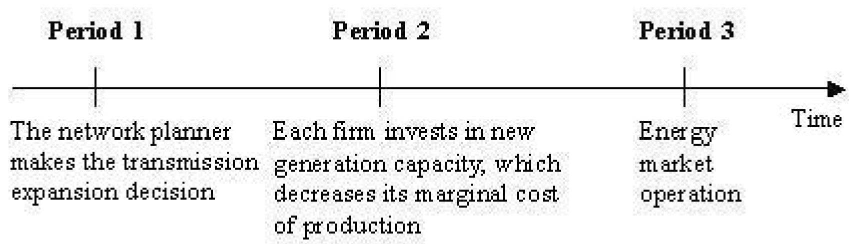


Figure 6: Three-period transmission investment model

The last period (period 3) represents the energy market operation. That is, in this period, we compute the equilibrium quantities and prices of electricity over given generation and transmission capacities determined in the previous periods. We model the energy market equilibrium in the topology of the transmission network through a DC approximation of Kirchhoff's laws. Specifically, flows on lines can be calculated by using the power transfer distribution factor (PTDF) matrix, whose elements give the proportion of flow on a particular line resulting from an injection of one unit of power at a particular node and a corresponding withdrawal at an arbitrary (but fixed) slack bus. Different PTDF matrices corresponding to different transmission contingencies, with corresponding state probabilities, characterize uncertainty regarding the realized network topology in the energy market equilibrium. We assume that generation and transmission capacities as well as demand shocks are subject to random fluctuations that are realized in period 3 prior to the production and redispatch decisions by the generators and the system operator. We further assume that the probabilities of all such credible contingencies are public knowledge.

In our model the energy market equilibrium in period 3 is characterized as a subgame with two stages. In the first stage, Nature picks the state of the world which determines the actual generation and transmission capacities as well as the shape of the demand and cost functions at each node. In

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[7] A "complete- and perfect-information" game is defined as a game in which players move sequentially and, at each point in the game, all previous actions are observable to the player making a decision.

the second stage, firms compete in a Nash-Cournot fashion by selecting their production quantities, while taking into consideration the simultaneous import/export decisions of the system operator whose objective is to maximize social welfare while satisfying the transmission constraints.

In the second period, each generation firm invests in new generation capacity, which lowers its marginal cost of production at any output level. For the sake of tractability we assume that generators' production decisions are not constrained by physical capacity limits. Instead we allow generators' marginal cost curves to rise smoothly so that production quantities at any node will be limited only by economic considerations and transmission constraints. In this framework, generation expansion is modeled as "stretching" the supply function so as to lower the marginal cost at any output level and thus increase the amount of economic production at any given price. Such expansion can be interpreted as an increase in generation capacity in a way that preserves the proportional heat curve or alternatively assuming that any new generation capacity installed will replace old, inefficient plants and, thereby, increase the overall efficiency of the portfolio of plants in producing a given amount of electricity. This continuous representation of the supply function and generation expansion serves as a proxy to actual supply functions that end with a vertical segment at the physical capacity limit. Since typically generators are operated so as not to hit their capacity limits (due to high heat rates and expansive wear on the generators) our proxy should be expected to produce realistic results. The return from the generation capacity investments made in period 2 occurs in period 3, when such investments enable the firms to produce electricity at lower cost and sell more of it at a profit. In our model, we assume that, in making their investment decisions in period 2, the generation firms are aware to the transmission expansion from period 1 and form rational expectations regarding the investments made by their competitors and the resulting market equilibrium in period 3. Thus the generation investment and production decisions by the competing generation firms are modeled as a two stage subgame perfect Nash equilibrium.

Finally, in the first period, the network planner which we model as a Stackelberg leader in this three-period game, evaluates different projects to upgrade the existing transmission lines while anticipating the generators' and the system operator's response in periods 2 and 3[8]. In particular, we consider here the case where the transmission planner evaluates a single transmission expansion decision but the proposed approach can be applied to more complex investment options.

Because the transmission planner under this paradigm anticipates the response by the generators, optimizing the transmission investment plan will determine the best way of inducing generation investment so as to maximize the objective function set by the transmission planner. We therefore will use the term *proactive network planner* to describe such a planning approach which results in outcomes that although they are still inferior to the integrated resource planning paradigm, they often result in the same investment decisions. In this paper, we limit the transmission expansion decision to expanding the capacity of any one existing line according to some specific transmission-planning objective. We assume the transmission expansion does not alter the original PTDF matrices, but only the thermal capacity of the line. This would be the case if, for the expanded line, we replaced all the wires by new ones (with new materials such as "low sag wire") while using the same existing high-voltage towers. Since the energy market equilibrium will be a function of the thermal capacities of all constrained lines, the Nash equilibrium of generation capacities will also be a function of these capacity limits. The proactive network planner, then, has multiple ways of influencing this Nash equilibrium by acting as a Stackelberg leader who anticipates the equilibrium of generation capacities and induces generation firms to make better investments.

We further assume that the generation cost functions are both increasing and convex in the amount of output produced and decreasing and convex in the generation capacity. Furthermore, as we mentioned before, we assume that the marginal cost of production at any output level decreases as

[8] No attempt is made to co-optimize transmission expansion and redispatch decisions. We assume that the transmission planning function treats the real time redispatch function as an independent follower (even if they reside in the same organization such as an ISO or RTO) and anticipates its equilibrium response as if it was an independently controlled entity with no attempt to exploit possible strategic coordination between transmission planning and real time dispatch. One should keep in mind, however, that such coordination might be possible in a for-profit system operator enterprise such as in the UK.

generation capacity increases. Moreover, we assume that both the generation capacity investment cost and the transmission capacity investment cost are linear in the extra-capacity added. We also assume downward-sloping linear demand functions at each node. To further simplify things, we assume no wheeling fees.

### 4.2 Model Notation

Sets:

- N: set of all nodes
- L: set of all existing transmission lines
- C: set of all states of contingencies
- $N_G$ : Set of generation nodes controlled by generation firm G
- $\mathcal{G}$ : Set of all generation firms

Decision variables:

- $q_i^c$: quantity generated at node i in state c
- $r_i^c$: adjustment quantity into/from node i by the system operator in state c
- $g_i$: expected generation capacity of facility at node i after period 2
- $f_\ell$ : expected thermal capacity limit of line $\ell$ after period 1

Parameters:

- $g_i^0$: expected generation capacity of facility at node i before period 2
- $f_\ell^0$: expected thermal capacity limit of line $\ell$ before period 1
- $g_i^c$: generation capacity of facility at node i in state c, given $g_i$

- $f_\ell^c$: thermal capacity limit of line ℓ in state c, given $f_\ell$
- $P_i^c(\cdot)$: inverse demand function at node i in state c
- $CP_i^c(q_i^c, g_i^c)$: production cost function of the generation firm located at node i in state c
- $CIG_i(g_i, g_i^0)$: cost of investment in generation capacity at node i to bring expected generation capacity to $g_i$.
- $CI_\ell(f_\ell, f_\ell^0)$: investment cost in line ℓ to bring expected transmission capacity to $f_\ell$.
- $\phi_{\ell,i}^c$: power transfer distribution factor on line ℓ with respect to a unit injection/withdrawal at node i, in state c.

**4.3 Model Formulation**

We start by formulating the third-period problem. In the first stage of period 3, Nature determines the state of the world, c. In the second stage, for a given state c, generation firm G ($G \in \mathsf{G}$) solves the following profit-maximization problem:

$$\begin{aligned} &\text{Max}_{q^c_{i\in N_G}} \quad \pi_G^c = \sum_{i\in N_G} P_i^c(q_i^c + r_i^c)\cdot q_i^c - CP_i^c(q_i^c, g_i^c) \\ &s.t. \qquad q_i^c \geq 0 \qquad , \quad i \in N_G \end{aligned} \tag{2}$$

Simultaneously with the generators' production quantity decisions, the system operator solves the following welfare maximizing redispatch problem (for the given state c):

$$\begin{aligned}
&\text{Max}_{\{r_i^c\}} \;\; \Delta W^c = \sum_{i \in N} \left( \int_0^{r_i^c} P_i^c(q_i^c + x_i)\, dx_i \right) \\
&s.t. \qquad \sum_{i \in N} r_i^c = 0 \\
&\qquad\quad -f_\ell^{\,c} \le \sum_{i \in N} \phi_{\ell,i}^{\;c} \cdot r_i^c \le f_\ell^{\,c} \qquad , \; \forall \ell \in L \\
&\qquad\quad q_i^{\,c} + r_i^{\,c} \ge 0 \qquad\qquad\quad , \; \forall i \in N
\end{aligned} \tag{3}$$

Given that we assume no wheeling fees, the system operator can gain social surplus, at no extra cost, by exporting some units of electricity from a cheap-generation node while importing them to other nodes until the prices at the nodes are equal, or until some transmission constraints are binding.

The previously specified model assumptions guarantee that both (2) and (3) are concave programming problems, which implies that first order necessary conditions (i.e. KKT conditions) are also sufficient. Consequently, to solve the period-3 problem (energy market equilibrium), we can just jointly solve the KKT conditions of the problems defined in (2), for all generation firms G, and (3) which together form a linear complimentarily problem (LCP), which can be easily solved with off-the-shelf software packages.

In period 2, each firm determines how much to invest in new generation capacity by maximizing the expected value of the investment (we assume risk-neutral firms) subject to the anticipated actions in period 3. Since the investments in new generation capacity reduce the expected marginal cost of production, the return from the investments made in period 2 occurs in period 3. Thus, in period 2, the firm G solves the following optimization problem:

$$\text{Max}_{g_{i \in N_G}} \;\; \sum_{i \in N_G} \{ E_c\left[\pi_i^c\right] - CIG_i(g_i, g_i^0) \} \tag{4}$$

$s.t$ KKT conditions of the problems defined in (2) for all $G \in \mathcal{G}$ and (3)

The problem defined in (4) is a Mathematical Program with Equilibrium Constraints (MPEC) problem and the problem of finding an equilibrium investment strategy for all the generation firms is an Equilibrium Problem with Equilibrium Constraints (EPEC), in which each firm solves an MPEC problem parametric on the other firms investment decisions and subject to the joint LCP constraints characterizing the energy market equilibrium in period 3. Unfortunately, this EPEC is constrained in a non-convex region and, therefore, we cannot simply write down the first order necessary conditions for each firm and aggregate them into a large problem to be solved directly.

As indicated earlier we consider here only the simple case where the network planner makes a single transmission expansion decision that will determine which line (among the already existing lines) it should upgrade, and what transmission capacity it should consider for that line, in order to optimize its transmission-planning objective. Thus, in period 1, the network planner solves the following optimization problem:

$$\begin{array}{ll} \text{Max}_{\ell, f_\ell} & \Phi(q_i^c, r_i^c, g_i, \ell, f_\ell) \\ s.t. & \text{Equilibrium solution of periods 2 and 3} \end{array} \tag{5}$$

where $\Phi(\cdot)$ represents the transmission-planning objective used by the network planner.

In the case where the transmission-planning objective is the expected social welfare, we have:

$$\Phi(q_i^c, r_i^c, g_i, \ell, f_\ell) = \sum_{i \in N} \left\{ E_c \left[ \int_0^{q_i^c + r_i^c} P_i^c(q)\, dq - CP_i^c(q_i^c, g_i^c) \right] - CIG_i(g_i, g_i^0) \right\} - CI_\ell(f_\ell, f_\ell^0)$$

**4.4 Transmission Investment Models Comparison**

Now, we like to compare the transmission investment decisions made by a *proactive network planner* (PNP) as defined above with the comparable decisions made by a *reactive network planner* (RNP), who plans transmission expansions by considering its impact on the energy market but without accounting for the generation investment response and its ability to influence such investments through the transmission expansion.

In the RNP model, the network planner selects the optimal location (among the already existing) and magnitude for the next transmission upgrade while considering the currently installed generation capacities. This case can be considered as a special case of the model described above where the generators are constrained in period 2 to select the same generation capacity that they already have. Thus, in period 1, the RNP solves the following optimization problem:

$$\begin{aligned} &\text{Max}_{\ell, f_\ell} \quad \Phi(q_i^c, r_i^c, g_i, \ell, f_\ell) \\ &s.t. \qquad \text{KKT conditions of the problems defined in (2), } \forall \text{ G, and (3)} \\ &\qquad\qquad g_i = g_i^0 \quad , \quad \forall \text{ i} \in \text{ N} \end{aligned} \tag{7}$$

In evaluating the outcome of the RNP investment policy we will consider, however, the generators' response to the transmission investment (which is suboptimal) and its implication on the spot market equilibrium.

By comparing (5) and (7), we observe that, if we eliminated the second-period problem conditions of each problem, then both problems would be identical. Thus, there exists a correspondence from generation capacities space to transmission capacities space, $f^*(g)$, that characterizes the "unconstrained" optimal investment decisions of both the PNP and the RNP. Since the second periods of both models are identically modeled, there also exists a correspondence from transmission capacities space to generation capacities space, $g^*(f)$, that characterizes the optimal decisions of generation firms under both the PNP and the RNP approach. The optimal solution of the PNP model is at the intersection of these two correspondences. That is, the transmission capacity chosen by the PNP, $f^*_{PNP}$, is such that $f^*(g^*( f^*_{PNP} ) ) = f^*_{PNP}$. On the other hand, the transmission capacity chosen by the RNP, $f^*_{RNP}$, is on the correspondence $f^*(g)$, at the currently installed generation capacities (i.e., $f^*_{RNP} = f^*(g^0)$ ). Thus, the optimal solution of the second period of the RNP model is on the correspondence $g^*(f)$, at transmission capacities $f^*_{RNP}$. Since the correspondence $g^*(f)$ characterizes the optimality conditions of the period-2 problem in the PNP model, any pair $(g^*(f), f)$ represents a feasible solution for the PNP model. Consequently, the optimal solution of the RNP model, $(g^*( f^*_{RNP}), f^*_{RNP})$, is a feasible solution of the PNP model. Therefore, the optimal solution of (5) cannot be worse than the optimal solution of (7).

Summarizing, under any transmission-planning objective, the optimal value obtained from the proactive network planner model is never smaller (worse) than the optimal value obtained from the reactive network planner model.

It is interesting to note that, although the previous result states that a RNP cannot do better than a PNP, the sign of the inefficiency is not evident. That is, without adding more structure to the problem, it is not evident whether the network planner underinvests or overinvests in transmission under the RNP model as compared to the PNP investment levels.

## 5. ILLUSTRATIVE EXAMPLE

We illustrate the results derived in the previous section with the simple three-node network displayed in Figure 7. We assume that each node has both local generation and local demand. Moreover, for simplicity, we consider three generation firms in the market (each firm owning the generators at a single node).

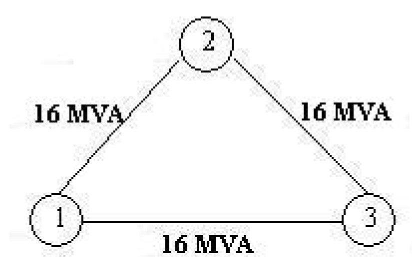


Figure 7: Three-node network used in our case study

We assume that the electric characteristics of the three transmission lines of the network in Figure 7 are identical. For these three transmission lines, the resistance is 0.15 p.u., the reactance is 0.3 p.u., and the thermal capacity rating is 16 MVA.

The uncertainty associated with the energy market operation is classified into five contingent states, as shown in table 1. Table 2 shows the nodal information in the normal state.

Table 1: States of contingencies associated to the energy market operation.

| State | Probability | Type of uncertainty and description |
|---|---|---|
| 1 | 0.80 | Normal state:<br>Data set as in table 2 |
| 2 | 0.05 | Demand uncertainty:<br>All demands increase by 20% |
| 3 | 0.05 | Demand uncertainty:<br>All demands decrease by 20% |
| 4 | 0.05 | Network uncertainty:<br>Line 1-2 goes down |
| 5 | 0.05 | Generation uncertainty:<br>Generator at node 3 goes down |

Table 2: Nodal information used in the three-node network in the normal state.

| Data type (units) | Information | Nodes where apply |
|---|---|---|
| Inverse demand function ($/MWh) | $P_i(q) = 50 - q$ | 1 |
| Inverse demand function ($/MWh) | $P_i(q) = 60 - q$ | 2 |
| Inverse demand function ($/MWh) | $P_i(q) = 80 - q$ | 3 |
| Generation cost function ($/MWh) | $CP_i(q_i, g_i) = (0.4 \cdot q_i^2 + 25 \cdot q_i) \cdot (g_i^0 / g_i)$ | 1, 2, and 3. |

We assume the same production cost function, $CP_i(q_i, g_i)$, for all generators. Note that $CP_i(q_i, g_i)$ is increasing in $q_i$, but it is decreasing in $g_i$. Moreover, recall that we have assumed that generators have unbounded capacity. Thus, the only important effect of investing in generation capacity is lowering the production cost. We also assume that all generation firms have the same investment cost function, given by CIGi $(g_i, g_i^0) = 6 \cdot (g_i - g_i^0)$, in dollars. The before-period-2 expected generation capacity at node i, $g_i^0$, is 60 MW (the same for all nodes). In our model, the choice of the parameter $g_i^0$ is not important because the focus of this work is not on generation adequacy. Instead, what really matters in our model is the ratio ($g_i^0$/ $g_i$) since we focus on the cost of generating power and the effect that both generation and transmission investments have on that cost.

As indicated earlier, the KKT conditions for the period-3 problem of the PNP model constitute a Linear Complementarity Problem (LCP). We solve it, for each contingent state by minimizing the complementarity conditions subject to the linear equality constraints and the non-negativity constraints. [9] The period-2 problem of the PNP model is an Equilibrium Problem with Equilibrium Constraints (EPEC), in which each firm faces a Mathematical Program subject to Equilibrium Constraints (MPEC). [10] We attempt to solve for an equilibrium, if at least one exists, by iterative deletion of dominated strategies. That is, we sequentially solve each firm's profit-maximization problem using as data the optimal values from previously solved problems. Thus, starting from a feasible solution, we solve for $g_1$ using $g_{(-1)}$ as data in the first firm's optimization problem (where $g_{(-1)}$ means all firms' generation capacities except for firm 1's), then solve for $g_2$ using $g_{(-2)}$ as data, and so on. We solve each firm's profit-maximization problem using sequential quadratic programming algorithms implemented in MATLAB®.

We test our model from a set of different starting points and using different generation-firms' optimization order. All these trials gave us the same results. For the PNP model, the optimal levels of generation capacity under absence of transmission investments are ($g_1$*, $g_2$*, $g_3$*) = (60.9, 119.7, 80.6), in MW. Table 3 lists the corresponding generation quantities ($q_i$), import/export quantities ($r_i$) and nodal prices ($P_i$) in the normal state.

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[9] Any LCP can be written as the problem of finding a pair of vectors $x, y \in \Re^n$ such that $x = q + M \cdot y$, $x^T \cdot y = 0$, $x \geq 0$, and $y \geq 0$, where $M \in \Re^{n \times n}$, $q \in \Re^n$. Thus, we can solve it by minimizing $x^T \cdot y$ subject to $x = q + M \cdot y$, $x \geq 0$, and $y \geq 0$. If the previous problem has an optimal solution where the objective function is zero, then that solution also solves the corresponding LCP.

[10] See (Yao et al., 2004) for a definition of both EPEC and MPEC.

Table 3: Generation quantities, adjustment quantities, and nodal prices in the normal state, under the PNP model.

| Node | $q_i$ (MWh) | $r_i$ (MWh) | $P_i$ ($/MWh) |
|---|---|---|---|
| 1 | 11.57 | -6.91 | 45.34 |
| 2 | 22.64 | -6.91 | 44.26 |
| 3 | 18.33 | 13.81 | 47.85 |

To solve the period-1 problem of the PNP model, we iteratively solve period-2 problems in which a single line has been expanded and, then, choose the expansion producing the highest expected social welfare. For simplicity, we do not consider transmission investment costs (it can be thought that the per-unit transmission investment cost is the same for each line upgrade so that we can get rid of these costs in the expansion decision). In this sense, our results establish an upper limit in the amount of the line investment cost. We tested the PNP decision by comparing the results of independently adding 16 MVA of capacity (doubling the actual line capacity) to each one of the three lines of the network in Figure 7. The results are summarized in table 4. In table 4, "Avg. L" corresponds to the average expected Lerner index[11] among all generation firms, "P.S." is the expected producer surplus of the system, "C.S." is the expected consumer surplus of the system, "C.R." represents the expected congestion rents over the entire system, "W" is the expected social welfare of the system, and "g*" corresponds to the vector of all Nash-equilibrium expected generation capacities.

Table 4: Assessment of single transmission expansions under the PNP model.

| Expansion Type | Avg. L | P.S. ($/h) | C.S. ($/h) | C.R. ($/h) | W ($/h) | *g** (MW) |
|---|---|---|---|---|---|---|
| No expansion | 0.388 | 907.1 | 633.5 | 55.3 | 1595.9 | [60.9; 119.7; 80.6] |
| 16 MVA on line 1-2 | 0.388 | 907.1 | 633.5 | 55.3 | 1595.9 | [60.9; 119.7; 80.6] |
| 16 MVA on line 1-3 | 0.439 | 852.0 | 724.5 | 58.4 | 1634.9 | [97.2; 116.6; 81.0] |
| **16 MVA on line 2-3** | **0.441** | **883.8** | **696.2** | **67.9** | **1647.9** | **[97.2; 99.5; 96.8]** |

[11] The Lerner index is defined as the fractional price markup i.e. (Price – Marginal cost) / Price.

From table 4, it is evident that the best single transmission line expansion (in terms of expected social welfare) that a PNP can choose in this case is the expansion of line 2-3. Now, we are interested in comparing the PNP decision with the decision that a RNP would take under the same system conditions. We tested the RNP decision by comparing the results of independently adding 16 MVA of capacity (doubling the actual line capacity) to each one of the three lines of the network in Figure 7. The results are summarized in table 5, where we use the notation $\overline{x}$ to represent the value of x as seen by the RNP.

Table 5: Assessment of single transmission expansions under the RNP model.

| Expansion Type | $\overline{\text{Avg. L}}$ | $\overline{\text{P.S.}}$ (\$/h) | $\overline{\text{C.S.}}$ (\$/h) | $\overline{\text{C.R.}}$ (\$/h) | $\overline{\text{W}}$ (\$/h) |
|---|---|---|---|---|---|
| No expansion | 0.280 | 918.8 | 422.4 | 70.2 | 1411.4 |
| 16 MVA on line 1-2 | 0.280 | 918.8 | 422.4 | 70.2 | 1411.4 |
| **16 MVA on line 1-3** | **0.281** | **909.3** | **489.4** | **23.1** | **1421.8** |
| 16 MVA on line 2-3 | 0.280 | 918.8 | 423.2 | 68.5 | 1410.5 |

From table 5, it is clear that the social-welfare-maximizing transmission expansion for the RNP is, in this case, to expand line 1-3. Thus, the true optimal levels of the RNP model solution are: Avg. L = 0.439, P.S. = $ 852.0 /h, C.S. = $724.5 /h, C.R. = $ 58.4 /h, W = $ 1634.9 /h, and g* = (97.2, 116.6, 81.0), in MW. By comparing table 4 and table 5, it is evident that the optimal decision of the PNP differs from the optimal decision of its reactive counterpart. Specifically, the PNP considers not only the welfare gained directly by adding transmission capacity (on which the RNP bases its decision), but also the way in which its investment induces a more socially efficient Nash equilibrium of expected generation capacities.

## 6. CONCLUSIONS AND FUTURE WORK

In this chapter we illustrated, through a simple radial-network example, how different planning objectives can result in divergent optimal expansions of a network. In particular, we showed that the maximization of social welfare, the minimization of local market power, the maximization of consumer surplus and the maximization of producer surplus can all result in divergent optimal expansions of a transmission network. Consequently, finding a unique politically feasible and fundable network expansion policy could be a very difficult, if not impossible, task. Accordingly, even if we agreed that a weighted sum of consumer surplus and producer surplus is the appropriated objective function to use, the weights to be used would be a controversial matter since different weights could lead to different optimal network expansions.

One of the key assumptions of the radial-network example presented in this chapter is that at least one of the generators can exercise local market power. Without considering local market power (that is, in a world where every generator faces a perfectly competitive market), the results and conclusions obtained here are not valid. However, given the prevalence of local market power in the power generation business, our results cannot be dismissed.

Motivated by the strong interrelationship between power generation and transmission investments, we have introduced a new transmission planning paradigm that attempts to capture some of the efficiency gains of integrated resource planning which is no longer feasible in an unbundled-market-based electricity industry. Our proposed approach employs a three-period model of transmission investments in which the transmission planner acts as a Stackelberg leader anticipating the effect of transmission expansion on generation investment and the subsequent energy market equilibrium. In this model, oligopolistic generation firms respond to transmission investments by interacting as Nash players in the generation investment game while anticipating the outcome of Cournot competition in the energy market.

Our future work will extend our three-period transmission investment model so that we can better characterize real-world power systems. An important extension is the analysis of our model when allowing the construction of lines at new locations (rather than upgrading existing lines). In this case, an expansion can change the electric properties of the network (and, thus, the PTDF matrices), which represents a more realistic scenario. Another valuable extension is the consideration of risk-averse generation firms. We expect to obtain more moderate generation investment levels when including risk aversion in the generation investment decisions.

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**APPENDIX**

In this appendix, we present the additional computations for the example proposed in section 2 of this chapter showing that the maximization of social welfare, the minimization of local market power, the maximization of consumer surplus and the maximization of producer surplus can all result in divergent optimal expansions of the transmission network. In particular, by altering the marginal cost of production at node 1, we show here that: i) the transmission expansion that maximizes total producer surplus can differ from the expansion that maximizes social welfare and from the expansion that maximizes consumer surplus in the same network, and ii) the transmission expansion that maximizes consumer surplus can differ from the expansion that maximizes social welfare in the same network.

Assume that $c_1$ = \$26 /MWh. Then, under the SSNS, the generation firm at node 1 optimally produces $q_1^{(SSNS)}$ = 120 MWh and charges $P_1^{(SSNS)}$ = \$38 /MWh. With this quantity and price, the producer surplus at node 1 is $PS_1^{(SSNS)}$ = \$ 1,440 /h and the consumer surplus at this node is $CS_1^{(SSNS)}$ = \$720 /h. The Lerner index at node 1 is $L_1^{(SSNS)}$ = 0.32.[12] Moreover, as in the case where $c_1$ = \$25 /MWh, under the SSNS, the firms at node 2 optimally produce an aggregate amount $q_2^{(SSNS)}$ = 69.6 MWh, and the market-clearing price is $P_2^{(SSNS)}$ = \$30.4 /MWh. Also, the producer surplus at node 2 is equal to $PS_2^{(SSNS)}$ = \$ 363 /h and the consumer surplus at this node is equal to $CS_2^{(SSNS)}$ = \$2,420 /h. [13]

Accordingly, the total producer surplus, the total consumer surplus, and the social welfare under the SSNS are $PS^{(SSNS)}$ = \$1,803 /h, $CS^{(SSNS)}$ = \$3,140 /h, and $W^{(SSNS)}$ = \$4,943 /h, respectively.

Under the ATCS, according to the Cournot-competition assumption, the monopolist at node 1 optimally produces $q_1^{(ATCS)}$ = 105 MWh while the competitive fringe at node 2 optimally produces $q_2^{(ATCS)}$ = 104 MWh (these output levels imply that there is a transmission flow of 39 MWh from node 2 to node 1). In this case, the market-clearing price is $P^{(ATCS)}$ = \$35.6 /MWh. With these new quantities and prices, the producer surplus at node 1 is $PS_1^{(ATCS)}$ = \$ 1,005 /h and the producer

[12] See footnote # 4.
[13] See footnote # 5.

surplus at node 2 is $PS_2^{(ATCS)}$ = \$ 807 /h.[14] As well, the consumer surpluses are $CS_1^{(ATCS)}$ = \$1,043/h for node 1's consumers and $CS_2^{(ATCS)}$ = \$2,076 /h for node 2's consumers. The new Lerner index at node 1 is $L_1^{(ATCS)} = 0.27$.

Assuming again that the transmission investment is made by an independent entity, the total producer surplus, the total consumer surplus, and the social welfare under the ATCS are equal to: $PS^{(ATCS)}$ = \$1,812 /h, $CS^{(ATCS)}$ = \$3,119 /h, and $W^{(ATCS)}$ = \$4,931 /h – investment costs, respectively.

Comparing the SSNS and the ATCS, we can observe that the expansion that maximizes total producer surplus is building a transmission line with "adequate" capacity (i.e., capacity greater than 39 MW). However, both the expansion that maximizes social welfare and the expansion that maximizes total consumer surplus are keeping each node as self-sufficient ( $W^{(ATCS)} < W^{(SSNS)}$, even if the investment costs were negligible, and $CS^{(ATCS)} < CS^{(SSNS)}$ ). That is, in the case where we have $c_1$ = \$26 /MWh, the construction of an adequate-capacity line decreases both social welfare and total consumer surplus while this network expansion maximizes total producer surplus. This analysis indicates that, as in the case of the simple example presented here (with $c_1$ = \$26 /MWh), the transmission expansion that maximizes total producer surplus in a particular network can be different from the expansion that maximizes social welfare and the expansion that maximizes total consumer surplus in the same network.

Now, assume that $c_1$ = \$24 /MWh. Then, under the SSNS, the monopolist at node 1 optimally produces $q_1^{(SSNS)}$ = 130 MWh and charges $P_1^{(SSNS)}$ = \$37 /MWh. With this quantity and price, the producer surplus at node 1 is $PS_1^{(SSNS)}$ = \$ 1,690 /h and the consumer surplus at this node is $CS_1^{(SSNS)}$ = \$845 /h. The Lerner index at node 1 is $L_1^{(SSNS)} = 0.35$.[15] Moreover, as in the previous cases, under the SSNS, the generation firms at node 2 optimally produce an aggregate amount $q_2^{(SSNS)}$ = 69.6 MWh, and the market-clearing price is $P_2^{(SSNS)}$ = \$30.4 /MWh. Also, the producer

[14] See footnote # 6.
[15] See footnote # 4.

surplus at node 2 is equal to $PS_2^{(SSNS)}$ = \$ 363 /h and the consumer surplus at this node is equal to $CS_2^{(SSNS)}$ = \$2,420 /h.[16]

Accordingly, the total producer surplus, the total consumer surplus, and the social welfare under the SSNS are $PS^{(SSNS)}$ = \$2,053 /h, $CS^{(SSNS)}$ = \$3,265 /h, and $W^{(SSNS)}$ = \$5,318 /h, respectively.

Under the ATCS, according to the Cournot-competition assumption, the monopolist at node 1 optimally produces $q_1^{(ATCS)}$ = 119 MWh while the competitive fringe at node 2 optimally produces $q_2^{(ATCS)}$ = 99 MWh (these output levels imply that there is a transmission flow of 33 MWh from node 2 to node 1). In this case, the market-clearing price is $P^{(ATCS)}$ = \$34.8 /MWh. With these new quantities and prices, the producer surplus at node 1 is $PS_1^{(ATCS)}$ = \$ 1,281 /h and the producer surplus at node 2 is $PS_2^{(ATCS)}$ = \$ 729 /h.[17] As well, consumer surpluses are $CS_1^{(ATCS)}$ = \$1,157 /h for node 1's consumers and $CS_2^{(ATCS)}$ = \$2,126 /h for node 2's consumers. The new Lerner index at node 1 is $L_1^{(ATCS)} = 0.31$.

Assuming again that the transmission investment is made by an independent entity, the total producer surplus, the total consumer surplus, and the social welfare under the ATCS are equal to: $PS^{(ATCS)}$ = \$2,010 /h, $CS^{(ATCS)}$ = \$3,283 /h, and $W^{(ATCS)}$ = \$5,293 /h – investment costs, respectively.

Comparing the SSNS and the ATCS, we can observe that the expansion that maximizes total consumer surplus is building a transmission line with "adequate" capacity (in theory, with capacity greater than 33 MWh). However, the expansion that maximizes social welfare is keeping each node as self-sufficient because $W^{(ATCS)} < W^{(SSNS)}$, even if the investment costs were negligible. This analysis makes evident that, as in the case of the example presented here (with $c_1$ = \$24/MWh), the transmission expansion that maximizes total consumer surplus in a particular network can be different from the expansion that maximizes social welfare in the same network.

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[16] See footnote # 5.
[17] See footnote # 6.