Transmission Planning and Operation in the Wholesale Market Regime

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1 Introduction

The wholesale market regime implies a dramatically different role for transmission planning and operation regulation relative to the former vertically-integrated monopoly regime. The monopoly supplier has the potential to capture any economies to scope between planning and operating the transmission network and building and operating all of the generation units connected to this transmission network because a single vertically-integrated firm performs all of these tasks. In contrast, suppliers in the wholesale market regime are typically financially independent of the transmission network owner and system operator and therefore condition their entry and operating decisions on the configuration of the transmission network.

This difference in the incentives generation unit owners face for locating and operating their units in the wholesale market regime versus the vertically-integrated monopoly regime has wide-ranging implications for the design and operation of the transmission network in the two regimes. The purpose of this paper is to explore these implications in order to adapt the transmission planning and operation regulatory process fully to the wholesale market regime, particularly one with a significant amount of intermittent renewables.

In the wholesale market regime, the configuration of the transmission network determines the extent of competition that suppliers face, with a more extensive transmission network facing suppliers with greater competition, which increases their unilateral incentive to submit offer prices closer to their marginal cost of production. This logic implies that a supplier owning low-cost generation capacity in a portion of the grid with limited transmission interconnection capacity to the remainder of the

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grid may find it expected profit-maximizing to withhold output from this capacity in order to raise the price it receives for the energy this capacity does supply. In contrast, a vertically-integrated, output price-regulated monopoly has little incentive to withhold output from low-cost units because this would only increase the total cost of serving demand throughout its service area with no corresponding revenue increase because the monopoly's revenues are the product of an output price set by the regulator and the realized demand at that price.

Because the configuration of the transmission network impacts the extent of competition that a supplier faces in the wholesale market regime, the transmission network configuration that leads to the lowest average price of electricity delivered to final consumers in the wholesale market regime is likely to require more capacity than the configuration of the transmission network that achieves this same outcome in the vertically-integrated monopoly regime. Below, I present two simple models to illustrate this point. This logic implies different measures of grid reliability in the two regimes—engineering reliability in the vertically-integrated monopoly regime and economic reliability in the wholesale market regimes.

The divergent roles of the transmission network in the two regimes arise from these two definitions of grid reliability. In the vertically-integrated monopoly regime, changes in the configuration of the transmission network can improve the performance of an *imperfectly regulated* vertically-integrated monopoly. In the wholesale market regime, changes in the configuration of the transmission network can improve the performance of an *imperfectly competitive* wholesale electricity market.

For each environment, it is only possible to obtain second-best solutions for the industry in the sense of Lipsey and Lancaster (1956), because certain features of the economic environment make it is impossible to implement the least-cost or first-best solution. For the vertically-integrated monopoly, a second-best solution is only possible because of the asymmetric information problem between the regulator and the monopolist. For the wholesale market regime, a second-best solution is only possible because large suppliers have the ability and incentive to exercise unilateral market power. Many studies have documented the fact that suppliers in wholesale electricity markets have the ability and incentive to exercise unilateral market power.[1]

This logic also implies that the "second-best" the optimal configuration of the transmission network depends on how transmission congestion is managed in the short-term market. Specifically, a single-pricing-zone wholesale market with a pay-as-bid mechanism for managing congestion implies a different least-cost-of-delivered-electricity transmission network configuration from a locational marginal pricing (LMP) wholesale market that integrates congestion management into the market mechanism.[2] A multiple-pricing-zone wholesale market design implies a

[1]For example, see Wolfram (1999) and Wolak and Patrick (2001) for the case of the England and Wales, Wolak (2000) for the case of Australia, Borenstein et al. (2002) and Wolak (2003b) for the case California, Bushnell et al. (2008b) for the PJM Interconnection, New England ISO, and California, and Wolak (2009) and McRae and Wolak (2014) for New Zealand.

[2]See Schweppe et al. (2013) for a detailed discussion of locational marginal pricing.

distinctly different least-cost-of-delivered electricity transmission network configuration from the ones that are least-cost for the single-zone or LMP market design.

The need to match the transmission planning and regulatory process to the wholesale market design requires a substantially more sophisticated transmission network planning process than the vertically-integrated monopoly regime. The transmission planner must recognize the fact that generation unit owners and load-serving entities will account for the current and future configuration of the transmission network in making their expected profit-maximizing entry and operating decisions. To this end, I outline a general forward-looking framework for evaluating transmission network expansions in the wholesale market regime. In the language of game theory, the transmission network planner should behave as a Stackelberg leader taking into account the best-reply entry and operating decisions of generation unit owners and load-serving entities in its planning and construction decisions.

The regulator's role of protecting consumers from retail electricity prices that reflect the exercise of unilateral market power in the wholesale market regime also implies a different criterion for measuring the economic benefits of a transmission expansion in the wholesale market regime versus the vertically-integrated monopoly regime. As Joskow (1974) notes, United States regulators set the vertically-integrated monopolist's output price to allow it the opportunity to recover all prudently incurred costs necessary to serve demand, including an adequate return on capital invested. Any transmission upgrade that reduces the total cost of serving demand throughout the utility's service territory more than the cost of the upgrade will allow the regulator to reduce the regulated price and should therefore be undertaken.

For the wholesale market regime, the regulator cannot ensure that generation unit owners receive output prices that only allow them to recover their prudently incurred costs. In the wholesale market regime, the regulator can only set prices for use of the transmission network and determine whether to allow revenue recovery for a transmission expansion. The extent of competition faced by each supplier determines whether the market price only recovers the incurred cost of that supplier. Because the configuration of the transmission network impacts the ability of suppliers to exercise unilateral market power which, in turn, impacts the wholesale electricity price, the regulator should account for the impact of the configuration of the transmission network on the ability and incentive of suppliers to exercise unilateral market power in deciding whether to approve a transmission expansion.

This logic implies an additional source of economic benefits from transmission expansions in the wholesale market regime besides simply reducing the production costs associated with serving demand. A transmission upgrade typically increases the extent of competition supplier's face, which then causes these suppliers to offer to supply energy at prices closer to their marginal cost of production. Lower offer prices lead to lower wholesale energy prices and lower total wholesale energy payments by electricity consumers. Consequently, in the wholesale market regime, if the total surplus increase to electricity consumers from an upgrade is less than the cost of the upgrade then the upgrade should be undertaken because it increases net surplus to electricity consumers.[3] A consumer benefits focus on regulating transmission planning and pricing in the wholesale market regime also argues for a competitive procurement process for an expansion determined by the planner. Joskow (2019) describes a recent experience with competitive transmission expansion procurement processes in the United States.

Because the wholesale market regime involves the risk that suppliers can exercise a substantial amount of unilateral market power in a relatively short period of time, there is likely to be significantly more uncertainty in the realized economic benefits of a transmission expansion.[4] Consequently, presenting a single point estimate of the economic benefits of a transmission expansion or a small number of scenario-based estimates, as is typically the case in the vertically-integrated monopoly regime, does not convey sufficient information about the range and likelihood of specific values of the realized benefits of transmission expansion in the wholesale market regime. This logic argues for presenting an estimated distribution of the realized economic benefits so that the regulator can fully assess the insurance value of the upgrade. To this end, I propose a general methodology for computing the distribution of realized economic benefits from an upgrade in the wholesale market regime.

Transmission network expansions can provide insurance against wholesale market outcomes that result in the exercise of significant unilateral market power or periods of local supply scarcity. It may, therefore, be prudent for a regulator to insure against these extreme market outcomes in the form of a transmission expansion, even if the expected realized benefit from an upgrade is less than the cost. The potential for large economic losses is the same reason that consumers purchase insurance against damages to their homes and car. For the same reason that consumers do not view the money for insurance against these large economic losses as wasted if this damage does not occur, regulators may feel the same way about insurance against market outcomes where a substantial amount of unilateral market power is exercised or local scarcity conditions arise. The insurance value of a transmission expansions is also likely to be even greater as the share of intermittent renewable generation in a region increases, because of the need to import more energy from neighboring control areas when within-region renewable energy production is low.

Both the competitiveness benefits and insurance value of the transmission expansions in the wholesale market regime argue for a transmission planning process over the entire interconnected transmission network because upgrading one link of an interconnected transmission network can change transfer capacities between many other parts of the transmission network. This logic implies the need for an inter-regional transmission network planning process to account for these economic

[3]The change in the variable cost of serving demand is not the relevant criteria in the wholesale market regime. Many upgrades that significantly reduce the ability of suppliers to exercise unilateral market power and therefore yield total surplus increases for consumers that are greater than the cost of the upgrade would not be undertaken by this criteria.

[4]Examples of wholesale markets where substantial amounts of unilateral market power was exercised are: California, Borenstein et al. (2002); New Zealand, Wolak (2009); and Colombia, McRae and Wolak (2016).

benefits, which is a substantial change relative to the state-level planning process in the United States and country-level planning process in other parts of the world.

Transmission expansions to support the deployment of renewable resources are also impacted by the paradigm shift in measuring the economic benefits of transmission expansions in the wholesale market regime. The location of rich sources of renewable resources is typically well-known and the only way for major load centers to access these resources is through transmission network interconnections between these renewable resource locations and major load centers. A forward-looking transmission planning process in a region with ambitious renewable energy goals should build transmission network interconnections between these regions and major load centers with sufficient interconnection capacity for the load centers to access these resources, anticipating the expected profit-maximizing entry decisions of investors in new renewable generation capacity. Again this planning process should take place over the geographic scope of the interconnected transmission network, not just at the state-level or country-level.

A final issue introduced by the wholesale market regime is the increased economic benefits associated with coordinating the planning of the transmission network over the largest possible geographic region and with the planning of the natural gas transmission network. The location of the natural gas transmission network capacity will influence the expected profit-maximizing location decisions of natural gas-fired generation unit owners. Consequently, a forward-looking and coordinated electricity transmission and natural gas transmission network planning process has the potential to increase the competitiveness of both wholesale electricity and natural gas markets.

The remainder of the paper proceeds as follows. The next section explains the distinction between engineering reliability and economic reliability. Section 3 demonstrates why these two criteria imply different optimal configurations of the transmission network. Specifically, the wholesale market regime typically requires more transmission capacity than the same industry structure under the vertically-integrated monopoly regime. Section 4 discusses the consequences of transmission planners and regulators continuing to rely on transmission expansion assessment methodologies from the former vertically-integrated monopoly regime. In particular, it becomes increasingly difficult to protect consumers from wholesale prices that reflect the exercise of unilateral market power, which reduces the likelihood consumers will realize benefits from electricity industry restructuring. Section 5 proposes a general transmission planning process for the wholesale market regime that is forward-looking, anticipating the profit-maximizing entry and operating decisions of generation unit owners. This planning process assumes a distribution of the future system conditions that impact the realized economic benefits from a transmission expansion. Section 6 argues that the wholesale market regime requires a substantially more sophisticated economic modeling framework for transmission planning relative to the vertically-integrated monopoly regime. This process should be broader in geographic scope and be coordinated with the input fuel infrastructure planning process and the location of renewable energy resources. This section also discusses the viability of a pure market-based approach to transmission planning and expansion where builders of transmission infrastructure finance projects from locational price differences. Section 7 argues that the distribution of the realized economic benefits from most transmission expansions in the wholesale market regime is significantly more positively skewed. This logic implies that transmission expansions provide insurance against these rare, but very costly events, which implies that a single point estimate for the economic benefits of a transmission expansion may not be as informative as the distribution of these realized benefits.

2 Grid Reliability in the Vertically-Integrated Monopoly Versus Wholesale Market Regime

The transmission planning process in an electricity supply industry with a formal wholesale market is fundamentally different from the process that existed when the industry was a vertically-integrated geographic monopoly that built and operated the transmission network, the portfolio of generation facilities, and the local distribution networks for a given geographic region. This difference is the result of the incentives faced by generation unit owners in the wholesale market regime versus the vertically-integrated monopoly regime.

A crucial determinant of the reliability of the transmission network in the vertically-integrated geographic monopoly regime is that a single firm owns, or at least controls, the operation of all generation resources available to serve final consumers in that geographic region. The second feature is the fact that the relevant regulatory authority prospectively sets the output price of the vertically-integrated monopoly and requires it to serve all demand at this price, which effectively makes the monopoly's total revenues invariant to how it serves this demand.

Consequently, the geographic monopoly market structure combined with retail price regulation eliminates many of the incentives for inefficient operation by generation unit owners that can arise in the wholesale market regime.[5] Because the revenues received by the vertically-integrated monopoly are largely independent of how it operates its generation units, a profit-maximizing monopolist has an incentive to operate its available generation units to minimize the cost of serving demand. This logic implies that in the vertically-integrated monopoly regime a transmission network is deemed to be reliable if there is sufficient capacity for the firm that owns and operates all of the generation units in the region and has interconnections with neighboring control areas to maintain a pre-specified level of reliability of the supply of electricity to final consumers.

This definition of reliability is based purely on engineering criterion because it assumes the transmission network, the fleet of generation units, and portfolio of supply contracts from outside of the control area are all owned and operated by the

[5]The vertically-integrated monopoly regime creates other sources of inefficiencies in generation investment and system expansion and operation not present in the wholesale market regime. Wolak (2014) describes the causes and consequences of these inefficiencies in the vertically-integrated and wholesale market regimes.

monopolist to serve demand in real-time. A grid that satisfies these criteria is said to meet the engineering standard for reliability.

In the wholesale market regime, the generation segment of the industry is open to competition, and the transmission network is operated as an open access facility for all generation unit owners and retailers. The regulator has a limited ability to specify where new generation facilities will be built or how new and existing generation facilities will be operated. Privately-owned generation unit owners are likely to build new facilities at the most profitable locations, which could be near a major load center and/or on the constrained side of congested transmission paths. Moreover, generation unit owners will offer their facilities into the short-term wholesale market and operate them to maximize the return to their shareholders from this investment taking into account the configuration of the transmission network and the mechanism used to price congestion in the transmission network.

For this reason, transmission planning and operation is now a crucial component of the wholesale market regime regulatory process because the configuration of the transmission network impacts the competitiveness of the wholesale electricity market. The regulator can protect electricity consumers from prices that reflect the exercise of significant unilateral market power through transmission expansions that increase the number of independent generation unit owners able compete to supply energy at each location in the transmission network. These upgrades make it less likely that a generation unit owner will find it unilaterally profit-maximizing to withhold output and congest the transmission network in order to increase the price it receives for the output that it sells.

Although many wholesale electricity markets, particularly those in the United States, have local market power mitigation mechanisms in place to limit the ability of suppliers to take advantage of the configuration of the transmission network in order to raise the price they receive for their output, these local market power mitigation mechanisms do not completely eliminate the incentive or ability of suppliers to exercise unilateral market power. Consequently, there is still likely to be a role for transmission expansions to increase the extent of competition suppliers face and thereby limit their ability and incentive to exercise unilateral market power.

The new role of the transmission planning and operation process in limiting the ability and incentive of market participants to exercise unilateral market power suggests a new definition of reliability for the wholesale market regime. An economically reliable transmission network has sufficient capacity to all locations in the transmission network so that suppliers at those locations face significant competition from enough independent suppliers to cause them to offer to supply energy at close to their marginal cost the vast majority of the hours of the year.

In the language of Wolak (2000), an economically reliable transmission network is one that faces all suppliers with very elastic residual demand curves the vast majority of hours of the year. As shown by Wolak (2000) for the case of Australia and McRae and Wolak (2014) for the case of New Zealand, the residual demand curve a supplier faces determines its ability to exercise unilateral market power in a formal wholesale market. The more firms that can compete to sell electricity at a supplier's location in the transmission network, the flatter is the residual demand curve that supplier faces. Increasing the capacity of a transmission network will typically increase the number of competitors a supplier faces and thereby flatten the distribution of residual demand curves that supplier faces.

Because of the role that transmission upgrades play in reducing the ability and incentive of suppliers to exercise unilateral market power in the wholesale market regime, the relevant planning standard in this regime is economic reliability. The first few years of operation in all of the restructured markets in the United States demonstrated that transmission networks that met the engineering reliability standards were insufficient to operate single-zone and multi-zone wholesale electricity markets. These markets experienced levels of transmission congestion not experienced in the former vertically-integrated regime, and this led to significant transmission network expansions and a shift to LMP market designs that price all transmission network and other relevant operating constraints in the day-ahead and real-time short-term markets.

3 Optimal Configuration of Transmission Network in the Vertically-Integrated Monopoly Versus Wholesale Market Regime

Because transmission expansions in the wholesale market regime limit the ability and incentive of suppliers to withhold output to raise wholesale electricity prices–an action that the vertically-integrated monopolist has little incentive to undertake–the optimal configuration of the transmission network in the wholesale market regime is likely to require more capacity than the optimal configuration in the vertically-integrated monopoly regime.

3.1 Second-Best Solutions for Monopoly and Wholesale Market Regimes

The first step in this argument must recognize that there is no single optimal transmission network configuration for both regimes. For the case of the vertically-integrated monopoly regime, the fact that the monopolist knows more about how to produce its output than the regulator implies the existence of informational asymmetries between the firm and regulator. As discussed in Wolak (1994), the regulator can only know the monopolist's incurred cost of producing its output, it can never know the least-cost way to produce the monopolist's output. This implies that transmission expansions in the vertically-integrated monopoly regime can only improve the performance of an imperfectly price-regulated monopoly. The regulator can only determine if a transmission expansion is likely to reduce the monopolist's incurred cost of serving demand more than the incurred cost of the transmission network expansion. Because of the informational asymmetries between the regulator and monopolist concerning the monopolist's cost of production, the regulator can never determine the least-cost configuration of the monopolist's transmission network.

For the case of the wholesale market regime, finding the least-cost transmission network configuration is impossible because the variable costs of generation units are not known by the transmission planner or system operator. In this regime, generation units are called upon to supply electricity based on offer prices, not variable costs. Even if the regulator knew each generation unit owner's minimum cost of production, it is extremely unlikely that all suppliers would find it unilaterally profit-maximizing to submit their minimum cost of supplying electricity as their offer price during all hours of the year. In all offer-based wholesale electricity markets, some generation unit owners have the ability and incentive to exercise unilateral market power during a number of hours of the year. This means that the resulting dispatch of generation units would not be the least-cost, and the transmission network that is optimal for the least-cost dispatch of generation units would not be the least cost to consumers for the case that suppliers exercised unilateral market power during those hours of the year. Consequently, at best, transmission expansions in the wholesale market regime can only improve the performance of an imperfectly competitive wholesale electricity market.

Therefore the optimal configuration of the transmission network in both regimes necessarily implies solving for a "second-best" transmission network configuration in the sense of Lipsey and Lancaster (1956). In the case of the vertically-integrated monopoly regime, the informational asymmetries about the monopolist's production process and the demand it faces between the firm and the regulator are the constraint that implies an optimal "second-best" solution. In the case of the wholesale market regime, the fact that wholesale electricity markets are not perfectly competitive and suppliers exercise unilateral market power implies an optimal "second-best" solution in the wholesale market regime.

3.2 Why Wholesale Market Regime Is Likely to Require More Transmission Capacity?

This section presents two simple models that illustrate the economic forces that imply the "second-best" optimal amount of transmission capacity for a region in the wholesale market regime is typically larger than that it is for the same region in the vertically-integrated monopoly regime. The first model focuses on the mechanism that more transmission capacity allows lower cost sources of electricity to supply more energy to final consumers. The second model focuses on the mechanism that more transmission capacity faces suppliers with the ability and incentive to exercise unilateral market power with a flatter residual demand curve.

For the first model suppose the wholesale market is composed of N identical firms, each with cost function $C(q, T) = c(T)q + F$, where q is the firm's output level, T is the amount of transmission capacity in the region, F is the fixed cost of production for the firm, and $c(T)$ is marginal cost of production, which is a decreasing function of T, $\mathrm{d}c(T)/\mathrm{d}T < 0$. This assumption implies that output level q can be supplied at a lower marginal cost with a larger value of T. For the case of the vertically-integrated monopoly regime, assume that $\mathrm{CI}(q, T) = \mathrm{ci}(T)q + \mathrm{FI}$, is the cost function for the vertically-integrated monopoly, where $\mathrm{ci}(T)$ is the incurred marginal cost of the vertically-integrated monopoly and FI is its incurred fixed cost. Let $P(q)$ equal the inverse demand curve for electricity and $\mathrm{TC}(T)$ is the total cost of transmission capacity T, where $\mathrm{dTC}(T)/\mathrm{d}T > 0$ and $d^2\mathrm{TC}(T)/\mathrm{d}T^2 > 0$, which implies that the total cost of transmission capacity is increasing at an increasing rate in T.

For the case of the vertically-integrated monopoly regime, the regulator is assumed to set the output price to maximize the sum of consumer and producer surplus subject to the monopolist recovering its incurred costs. This yields the following constrained optimization problem:

$$\mathrm{Max}_{\{q,T\}} \int_0^q P(s)\mathrm{d}s - \mathrm{CI}(q, T) - \mathrm{TC}(T) \text{ subject to } P(q)q - \mathrm{CI}(q, T) - \mathrm{TC}(T) = 0$$

An equivalent form of this problem maximizes consumer surplus subject to the monopolist recovering its incurred costs:

$$\mathrm{Max}_{\{q,T\}} \int_0^q P(s)\mathrm{d}s - P(q)q \text{ subject to } P(q)q - \mathrm{CI}(q, T) - \mathrm{TC}(T) = 0$$

The solution to either of these problems satisfies the following first-order conditions:

$$\begin{aligned} &(P - \mathrm{ci}(T))/P = -k/\varepsilon, \\ &-q(\mathrm{dci}(T)/\mathrm{d}T) = \mathrm{dTC}(T)/\mathrm{d}T, \\ &\text{and } P(q)q - \mathrm{CI}(q, T) - \mathrm{TC}(T) = 0, \end{aligned}$$

where $1 > k > 0$ and ε is the own-price elasticity of demand for electricity. The first equation is the standard Ramsey-pricing result that requires marking up the output price above marginal cost in order to recover sufficient revenues to cover the monopolist's fixed costs, FI, and $\mathrm{TC}(T)$. The second equation sets the marginal generation cost reduction equal to the marginal transmission cost increase from a one-unit change in T. The third equation requires that total revenues equal total incurred costs. Note that k lies in the interval (0,1) if unrestricted monopoly pricing would recover more revenues than the firm's incurred costs, a likely outcome in the electricity supply industry.

For the case of the wholesale market regime, I still assume that the regulator would like to maximize consumer surplus. However, the regulator can no longer set the output price to achieve this outcome. Competition among suppliers in the wholesale market sets the market-clearing price. I assume price is set by quantity-setting competition among the N producers. As shown in Waterson (1984), equilibrium in this market implies the following relationship between the market price, the marginal cost of each firm, the own-price elasticity of the market demand, and the number of firms in the market: $(P - c(T))/P = -1/(N\varepsilon)$, with each firm producing $q_i = q/N$.

This logic implies that the regulator knows that once the value of T is set, the value of q will be determined by quantity-setting competition among the N suppliers. Applying the implicit function theorem to $(P(q(T)) - c(T)) = -P(q(T))/(N\varepsilon)$ and making the simplifying assumption that ε, the price elasticity of demand is constant ($P(q) = Aq^{1/\varepsilon}$), implies

$$\frac{\mathrm{d}q(T)}{\mathrm{d}T} = \frac{\frac{\mathrm{d}c(T)}{\mathrm{d}T}}{P'(q(T))\left(1 + \frac{1}{N\varepsilon}\right)}$$

and $\mathrm{d}q(T)/\mathrm{d}T > 0$, because $\mathrm{d}c(T)/\mathrm{d}T < 0$, $P'(q) < 0$ and $(1 + 1/(N\varepsilon)) > 0$ in order for a quantity-setting oligopoly equilibrium to exist.

Similar to the vertically-integrated monopoly regime, the regulator chooses the transmission network capacity to maximize consumer surplus less than the cost of the transmission grid. Different from the vertically-integrated monopoly regime, the regulator must respect the constraint that industry output and the market-clearing price are determined from quantity-setting competition. This yields the following optimization problem for the regulator:

$$\mathrm{Max}_{\{T\}} \int_0^{q(T)} P(s)\mathrm{d}s - P(q(T))q(T) - \mathrm{TC}(T).$$

Using the above definition of $\mathrm{d}q(T)/\mathrm{d}T$, the first-order condition in T reduces to:

$$-q\frac{\frac{\mathrm{d}c(T)}{\mathrm{d}T}}{\left(1 + \frac{1}{N\varepsilon}\right)} = \frac{\mathrm{dTC}(T)}{\mathrm{d}T}.$$

Note that because $(1 + 1/(N\varepsilon)) < 1$, if $\mathrm{ci}(T) = c(T)$ for all T (the vertically-integrated monopoly's incurred marginal cost is equal to the marginal cost of each of the N symmetric firms in the wholesale market regime), the optimal value of T under the wholesale market regime is greater than the optimal value of T under the vertically-integrated monopoly regime. This result follows from the fact that the second derivative of $\mathrm{TC}(T)$ is positive.

The first-order condition for T for the wholesale market regime illustrates the competitiveness benefits of transmission upgrades in this regime, because more transmission capacity reduces marginal cost of supplying output for each of N the firms, which lowers the output price paid by consumers. Therefore, for the same value of T, the marginal benefit, $\mathrm{MB}(T)$, of an additional unit of transmission capacity is larger under the wholesale market regime than the vertically-integrated monopoly regime. Specifically,

$$\mathrm{MB}(T)|_{\text{Wholesale}} = -q\frac{\frac{\mathrm{d}c(T)}{\mathrm{d}T}}{\left(1+\frac{1}{N\varepsilon}\right)} > \mathrm{MB}(T)|_{\text{Vertically-Integrated}} = -q\frac{\mathrm{dci}(T)}{\mathrm{d}T}.$$

A second model introduces an additional channel through which the competitiveness benefits can be realized. The vertically-integrated monopoly solution is the same as above, but for the wholesale market regime assume that the monopoly is divested in such a way that $K < N$ firms own a sufficient amount of generation capacity to be able to set quantity strategically and the remaining $N - K$ firms behave as a price-takers. Let SO(p, T) equal the supply curve of these-price-taking firms and assume that $\partial \mathrm{SO}(p, T)/\partial p > 0$, $\partial \mathrm{SO}(p, T)/\partial T > 0$ and $\partial^2 \mathrm{SO}(p, T)/\partial T/\partial p > 0$, which implies that the supply curve is increasing in price, increasing in the amount of transmission capacity into regions where the K strategic firms compete, and increases in T increase the output responsiveness to the market price of the price-taking firms.

The remaining K firms are symmetric with a marginal cost equal to $c(T)$, where $\mathrm{d}c(T)/\mathrm{d}T < 0$ implies that more transmission capacity increases their ability to sell output from lower marginal cost units. Define $\mathrm{DR}(p, T) = D(p) - \mathrm{SO}(p, T)$ as residual demand faced by these K strategic firms, where $D(p)$ is the demand function associated with the inverse demand curve, $P(q)$. The first-order conditions for the symmetric quantity-setting competition equilibrium between the K strategic firms facing the residual demand curve, DR(p, T) is equal to:

$$(P - c(T))/P = -1/(K\eta(P, T)),$$

where $\eta(P, T) = (P/\mathrm{DR}(P, T)) * (\partial \mathrm{DR}(P, T)/\partial p)^{-1}$, is the price elasticity of this residual demand curve. The regulator knows that once T is chosen, competition among the K strategic firms and the $N - K$ price-taking firms yields a market-clearing price that solves the equation

$$P(T) - c(T) = -P(T)/(K\eta(P(T), T)).$$

Applying the implicit function theorem to this equation yields:

$$\frac{\mathrm{d}P(T)}{\mathrm{d}T} = \frac{\mathrm{d}c(T)/\mathrm{d}T + (\partial\eta(P, T)/\partial T)P(T)/(K\left[\eta(P(T), T)\right]^2)}{1 + \frac{1}{K\eta(P(T), T)} - \{P(T)/(K\left[\eta(P(T), T)\right]^2)\}\partial\eta(P, T)/\partial P}.$$

The regulator's problem for setting the optimal transmission network capacity then becomes:

$$\mathrm{Max}_{\{T\}} \int_0^{D(P(T))} P(s)\mathrm{d}s - D(P(T))P(T) - \mathrm{TC}(T)$$

Using the above expression for dP(T)/dT and the fact that $D(P(T)) = q$, the first-order condition in T reduces to

$$\frac{\mathrm{d}TC(T)}{dT} = -q\left\{\frac{\mathrm{d}c(T)/\mathrm{d}T + (\partial\eta(P,T)/\partial T)P(T)/(K\left[\eta(P(T),T)\right]^2)}{1+\frac{1}{K\eta(P(T),T)} - \{P(T)/(K\left[\eta(P(T),T)\right]^2)\}\partial\eta(P,T)/\partial P}\right\}$$

It can be shown that our assumptions on SO(p, T) implies, $\frac{\partial\eta(P,T)}{\partial T} < 0$, meaning that increasing T makes the residual demand curve facing the duopolists more price responsive. For simplicity, if we assume that $\partial\eta(P,T)/\partial P = 0$, elasticity of the residual demand curve facing the duopolists does not change as the price changes, then the first-order condition simplifies to:

$$\frac{\mathrm{dTC}(T)}{\mathrm{d}T} = -q\frac{\mathrm{d}c(T)}{\mathrm{d}T}\left\{\frac{1+\frac{\partial\eta(P,T)/\partial T)P(T)/(K\left[\eta(P(T),T)\right]^2)}{\mathrm{d}c(T)/\mathrm{d}T}}{1+\frac{1}{K\eta(P(T),T)}}\right\}.$$

The term $\left\{\frac{1+\frac{\partial\eta(P,T)/\partial T)P(T)/(K\left[\eta(P(T),T)\right]^2)}{\mathrm{d}c(T)/\mathrm{d}T}}{1+\frac{1}{K\eta(P(T),T)}}\right\}$ is greater than one because the numerator is greater than one and the denominator is less than one. This implies that if $c(T) = \mathrm{ci}(T)$, the optimal transmission capacity for the wholesale market regime is greater than optimal capacity in the vertically-integrated monopoly regime.

These two examples demonstrate that as long as there is imperfect competition in the wholesale electricity market, there will be a difference between the "optimal second-best" transmission network configuration in the wholesale market regime and the vertically-integrated monopoly regime. That is because increasing transmission capacity increases the extent of competition suppliers with the ability to exercise unilateral market power face, a source of consumer surplus increase not present in the vertically-integrated monopoly regime.

4 Consequences of Continuing to Rely on Methodologies from the Vertically-Integrated Monopoly Regime

The analysis of the previous section demonstrates that an important difference between transmission planning in the vertically-integrated monopoly regime and the wholesale market regime is that the regulator controls the firm's price and output level. The classical regulatory bargain is that if the regulator sets a price that allows the firm an opportunity to recover its costs, the firm must satisfy all demand at the regulated price. The configuration of the transmission network impacts the regulated firm's incurred cost of supplying this output, so it is optimal to invest in transmission capacity until the marginal benefit of lower production costs to serve demand from an additional unit of transmission capacity, $-q\mathrm{dci}(T)/\mathrm{d}T$, equals the marginal cost of an additional unit of transmission capacity, $\mathrm{dTC}(T)/\mathrm{d}T$.

In the wholesale market regime, output prices are determined by the competition between imperfectly competitive suppliers. The regulator only knows that once the capacity of transmission network is chosen, firms will make their entry decisions and set their output levels to maximize profits given this transmission capacity. Therefore, the "optimal second-best" transmission capacity should maximize consumer surplus less the cost of this transmission capacity accounting for the fact that all suppliers will maximize profits given this choice of transmission capacity. Specifically, the transmission planner chooses the value of the transmission capacity accounting for the expected profit-maximizing responses of all suppliers to this choice. This outcome will typically result in the regulator selecting a larger value of transmission capacity because of the improvements in market performance, as measured by market prices closer to marginal cost, resulting from the additional transmission capacity.

The different industry structures and the desire of the regulator to protect consumers from prices that reflect the exercise of market power imply different approaches to valuing transmission network investments. In case of the vertically-integrated utility, the regulator prospectively sets an output price to recover all of the costs—generation, transmission, distribution, and retailing—that the utility incurs to serve its customers. In addition, because the regulator sets the utility's output price, or more generally, the utility's revenue, to recover the utility's total production costs, the relevant welfare criteria for transmission planning is to maximize consumer surplus subject to the utility receiving an output price that allows it an opportunity to recover its incurred cost. This objective implies that if the incurred cost of serving load is reduced more than the cost of the transmission expansion, this upgrade should be undertaken.

The major challenge facing the regulator in the vertically-integrated regime is making the firm's incurred cost of production equal to the minimum cost of producing its output. Because of the asymmetric information problem between the firm and the regulator, solving this problem will result in the regulated firm earning some informational rents. This means that the price paid by consumers will be above that necessary to recover the minimum cost of producing the firm's output because the regulator is legally bound (at least in the United States) to set a price that allows the monopoly the opportunity to recover all prudently incurred costs associated with serving demand.[6]

For the wholesale market regime, the regulator provides no guarantee of cost recovery for the suppliers and has a limited ability to prevent suppliers from earning revenues substantially in excess of their production costs, including an adequate return on capital invested. The regulator can only set the market rules and participate in the transmission planning process. Transmission prices remain regulated in the wholesale market regime in the sense that the prices charged to consumers must allow the transmission network owner the opportunity to recover its costs. For this reason, the relevant welfare criterion is consumer surplus net of the cost the transmission network, because transmission costs must be recovered regardless of market outcomes in the wholesale market (assuming the transmission network is prudently operated).

[6] Wolak (1994) provides an estimate of the magnitude of these information rents for the case of regulated water utilities in California.

Although the regulator cannot set the price paid to suppliers, its choice of the capacity of the transmission network does impact equilibrium outcomes in the wholesale market, as the examples in the previous section demonstrated. This logic implies that the transmission planning process now serves a regulatory function in the sense of protecting consumers from the exercise of unilateral market power. In particular, if a transmission network upgrade increases consumer surplus (because increased competition in the wholesale electricity market) more than the cost of the transmission upgrade, then the transmission upgrade should be undertaken in the wholesale market regime.

In this regime, the impact of a transmission network upgrade on the cost that suppliers incur in producing their output, is largely irrelevant to the valuation of an upgrade.[7] This is because wholesale prices are based on offers to supply energy into the short-term market, not the cost of supplying this energy. As Wolak (2000, 2003c, 2007) demonstrates, the expected profit-maximizing offers of a supplier with the ability to exercise unilateral market power depend on its cost of producing output and the extent of competition the supplier faces. A supplier's offer curve can be vastly different from its marginal cost curve if it does not face sufficient competition. Although there are explicit forms of regulatory intervention into market mechanisms such as market power mitigation mechanisms, offer caps, and price caps to limit the ability of suppliers to exercise unilateral market power in the wholesale market regime, these mechanisms do not completely eliminate the exercise of unilateral market power or the ability of transmission expansions to limit the ability of suppliers to exercise unilateral market power.

The following chain of logic determines how the benefits of transmission expansions should be assessed in the wholesale market regime. The benefits of an upgrade depend on its impact on wholesale market prices. Market prices depend on the offers suppliers submit into the short-term market and these offers depend on the configuration of the transmission network. Consequently, the planning process should be forward-looking in the sense of anticipating the expected profit-maximizing responses of market participants to the capacity and configuration of the transmission network, because this impacts the expected profit-maximizing behavior of suppliers with the ability to exercise unilateral market power.

Taking this argument further, in the wholesale market regime, the entry decisions of market participants depend on the characteristics of the transmission network. By recognizing and anticipating the profit-maximizing entry as well as the offer behavior response of generation unit owners to a given transmission upgrade, greater system-wide benefits from all transmission expansions can be realized.

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[7] Further, evidence for the irrelevance of a supplier's production costs to valuing transmission expansions in the wholesale market regime is the fact that these costs are largely unobservable in the wholesale market regime. Suppliers do not make detailed accounting costs filings with the regulator, as is the case in the vertically-integrated monopoly regime. Moreover, the goal of a wholesale market regime is to make the market sufficiently competitive that suppliers find it unilaterally expected profit-maximizing to submit offers into the short-term market close to their minimum marginal cost of production. Unfortunately, this goal has proven difficult, if not impossible, to obtain during all hours of the year in any wholesale electricity market.

There is a considerable first-mover benefit that electricity consumers receive from a transmission expansion policy that leads to new generation entry decisions, because transmission projects typically take significantly longer to plan, site, and construct than most new generation investments. For this reason, transmission expansions should lead rather than follow generation entry decisions.

Consider a wholesale electricity market contemplating a change in the transmission network configuration. If the planner chooses the new transmission configuration taking into account how this configuration will impact the future entry and operating decisions of generation unit owners, it can make any amount of spending on transmission investments more effective at reducing the ability of suppliers to exercise unilateral market power in the short-term market. The frequency of abnormally high market prices, out-of-merit energy costs, and other reliability costs can be significantly reduced if the transmission planning process is forward-looking and anticipates where new entry is likely to take place and how suppliers will operate given the configuration of the transmission network.

In contrast, a transmission expansion policy that responds to new generation investment decisions puts the planning and construction process in a continual game of catch-up with the entry decisions of new generation unit owners, because of the longer time it takes to plan, site and construct transmission facilities versus generation units. Such a policy would very likely result in higher average retail electricity prices to consumers because it would preclude consideration of many transmission expansions that provide access to low-cost distant generation in favor of the construction of generation units local to load centers.

Because the planning process must address current conditions in the transmission network before they create significant reliability problems, many longer horizon transmission expansions must be removed from consideration in a planning process that is not forward-looking. Only new local generation units can be considered given the short time horizon available to address the reliability concern. This implies that the wholesale market will have to rely increasingly on local market power mitigation mechanisms and other regulatory interventions to prevent generation unit owners from exercising the local market power associated with their location in the transmission network. These suppliers face inadequate competition for their output given the limited amount of transmission capacity into these load centers. Consequently, the regulatory interventions necessitated by a transmission expansion policy that responds to generation entry decisions severely limits the benefits accruing to consumers from wholesale electricity competition.

Any uncertainty about proposed transmission upgrades becoming a reality provides an opportunity for existing suppliers to exercise unilateral market power in the forward market. In the above example, if market participants do not believe that a proposed transmission upgrade will take place within two years, distant electricity suppliers are no longer credible competitors to the suppliers near the load center served by the retailer. Because of this delay, retailers can expect to pay a higher price for a forward contract for electricity that begins delivery two years in the future because of the reduced level of competition faced by suppliers providing this energy.

A transmission expansion policy that serves the interests of electricity consumers should create a level playing field for all generation sources to compete to provide the lowest-priced electricity at all delivery horizons. For example, distant generation from oil sands cogeneration, coal, or nuclear units can compete with natural gas-fired generation units located close to the major load centers only if there is sufficient transmission capacity to allow this to occur. Because there is considerable uncertainty over future fossil fuel prices and the price of GHG emissions, a transmission policy that allows all electricity generation technologies to interconnect and compete to supply energy to the major load centers will ensure that electricity consumers have access to the full range of available sources of electricity at all delivery horizons.

An efficient transmission expansion policy maximizes the competitiveness of the forward market for energy at all delivery horizons. However, different from the short-term market for energy, the actual transmission capacity does not need to exist when a forward contract is negotiated in order to discipline the behavior of suppliers in the forward market. Participants must only be confident that the capacity will exist when it is necessary for the seller of the forward contract to deliver energy. For example, suppose that a retailer is negotiating a forward contract for energy to be delivered several years in the future. A distant source of energy will discipline the offers of suppliers near the load center served by the retailer if all parties believe that the transmission capacity between this distant source of energy and the load center will exist when the contract begins delivering energy. For example, if the retailer is negotiating a contract that will begin delivery in two years, then it is only necessary that all market participants believe that the transmission capacity will be operating within two years. This logic emphasizes that the benefits of a forward-looking transmission expansion policy accrue to purchasers of electricity at all horizons to delivery when upgrades take place on time and according to plan.

The sequence of events that arise from transmission investments following generation investments is broadly consistent with outcomes in a number of United States wholesale electricity markets that do not have forward-looking transmission expansion policies. Transmission expansions are undertaken largely in response to new generation entry decisions rather than in anticipation of these entry decisions. These wholesale markets have experienced increasing amounts of transmission congestion, with growth rates in excess of the rate of growth of system load. The frequency and incidence of local market power problems have necessitated increasing reliance on local market power mitigation mechanisms, which typically set market-clearing prices based on loosely regulated variable costs of production of the mitigated generation units. The lack of a forward-looking transmission expansion policy that recognizes that the transmission network configuration plays a major role in allowing suppliers to exercise unilateral market power in wholesale electricity markets in many parts of the United States. Many transmission projects that would satisfy the regulatory test for in approval wholesale market regime will not be approved using a planning methodology designed for the wholesale market regime, thereby limiting the potential benefits consumers can realize from electricity industry restructuring.

5 A Methodology for Evaluating Transmission Expansions in the Wholesale Market Regime

Because the benefits of a transmission expansion depend on market prices and market prices are driven by inputs costs and the extent of competition suppliers face, there is considerably more uncertainty in the distribution realized benefits of transmission expansions in the wholesale market regime relative to the vertically-integrated monopoly regime, where the major source of uncertainty is the future cost of producing energy by the vertically-integrated monopoly. This section outlines a forward-looking methodology for evaluating transmission expansions in the vertically-integrated regime that accounts for the increased uncertainty in the realized benefits of these projects in the wholesale market regime.

5.1 Modeling Challenges in the Wholesale Market Regime

The ideal methodology for evaluating transmission upgrades is an equilibrium model with multiple strategic generation owners bidding for the right to supply electricity each hour of the day through a transmission network model that reflects the physical realities of system operation under any potential realization of future system conditions such as demand, input prices, hydrology and other factors that impact supplier behavior. With this methodology, market outcomes could be simulated with and without the proposed transmission upgrade for a large number of realizations from the distribution of future system conditions. Any decision criteria for determining whether to go forward with a proposed transmission upgrade will be a function of the distributions of market outcomes with and without the upgrades. With this modeling tool in hand, the planner/regulator could evaluate the viability of any potential transmission upgrade.

However, given the current state of economic theory and computing power, this methodology cannot be implemented without making significant modeling compromises. Specifically, even solving for the equilibrium day-ahead bidding/scheduling/congestion management strategy for only two firms owning multiple generating facilities in accordance with the California market rules (specifically, ten price and quantity bid increments for each generating facility, each of which can change on an hourly basis each day) is an extremely complex problem, even for the case in which there is no underlying transmission network model constraining the set of feasible production levels of generation unit owners. The strategy space for each player is enormous. In the day-ahead energy scheduling and congestion management process, this means setting the values of more than 500 parameters each day for each generating unit. A firm that owns 8 units, which is similar to the number owned by several California market participants, would have a 4000-dimensional strategy space.

Wolak (2000) has implemented a procedure for computing the expected profit-maximizing price and quantity offers of a single supplier in the Australian electricity market given the offer behavior of its competitors and the distribution of system demand. Computing this best-reply bidding strategy for a single day requires solving a roughly thousand parameter nonlinear programming problem subject to linear equality constraints. Computing an equilibrium with two firms setting-expected profit-maximizing offer curves would require solving a massive nonlinear complementary problem involving thousands of choice variables.

Determining the equilibrium strategies of firms operating in a wholesale electricity market in a manner that reflects the actual market rules and the actual size of each firm's strategy space increases the computational complexity to the point of being impossible to solve in a reasonable period of time. This conclusion is valid without attempting to account for the configuration of the transmission network in the wholesale market model. In general, computing a Nash equilibrium requires solving an extremely large nonlinear complementary problem subject to equilibrium constraints. Any attempt to account for the constraints on generation unit owner behavior implied by the physical configuration of the network massively increases computational complexity.

Because the purpose of the proposed methodology is to assess the benefits of transmission upgrades, adding a realistic network model is essential to achieving that goal. Unfortunately, firms competing through a transmission network with finite capacity can create discontinuities in the profit function of one firm with respect to the strategies of other firms, even in a two-node network model with two suppliers, as shown by Borenstein et al. (2000). This property implies that small changes in the behavior of one firm can lead to large changes in the best-reply of the other firm, which makes computing equilibrium strategies using standard techniques impossible. Both the enormity of the strategy space and the complications introduced by having firms compete through a realistic transmission network make solving the ideal model virtually impossible given the current state of computing power and solution methods.

Consequently, in order to make progress on this question, some economic modeling compromises must be made. Taking stock of what is actually feasible computationally and what is available in terms of historical data on the performance of a wholesale market available from the system operator, the following simplification seems to balance the goals of realism and tractability. All system operators have network models available that can compute market outcomes given the bids and schedules submitted by all market participants. These system operators also have a number of years of data available on offer behavior as a function of market conditions. The proposed simplified methodology is to use the current model of the transmission network with and without the upgrade and data on historical offer behavior and system conditions to analyze the potential benefits of a transmission upgrade.

5.2 A General Forward-Looking Methodology

An outline of this methodology follows. Let θ_{d} denote the firm's action choice for day d. This K-dimensional vector is composed of all of the parameters that a supplier submits to the system operator expressing its willingness to sell energy from each unit it owns each hour of the day. This vector is composed of the start-up cost, no-load cost, and the price and quantity parameters of the energy offer curve for each generation unit owned by the firm, assuming each of these offer parameters exists for the market under consideration. As noted above, the value of K can easily be in the thousands. Let Ω_{d} denote the set of variables known to the firm at the start of day d that it conditions its offers on. These variables could include: the load forecasts for all hours of the day, the temperature forecasts for the day at various locations in the control area, the demand for operating reserves, the price of natural gas and other input fuels, measures of water availability for hydroelectric units, and the amount of generating capacity owned by other firms within some radius of the plants owned by this firm, and most importantly for our purposes, the amount of available transmission capacity at various interfaces in the control area.

Let $\pi(\theta_{\mathrm{d}}|\Omega_{\mathrm{d}})$ denote the realized profits of the firm for day d given Ω_{d}. To compute this magnitude the supplier solves following optimization problem in θ_{d} for day d given the set of conditioning variables, Ω_{d},

$$\max_{\{\theta_{\mathrm{d}}\}} E(\pi(\theta_{\mathrm{d}}|\Omega_{\mathrm{d}}) \text{ subject to } h(\theta_{\mathrm{d}}) \leq 0,$$

where $h(\theta)$ is vector-valued function defining the set of technological and market rule constraints that restrict the values of θ_{d} that the firm can choose. The solution to this problem yields the expected profit-maximizing value θ_{d} as a function of the variables in Ω_{d}. Re-write the optimal value of θ_{d} as the vector-valued function $f(\Omega_{\mathrm{d}})$. Because both θ_{d} and Ω_{d} are observable, we can approximate the function $f(\Omega_{\mathrm{d}})$, as a very high-order polynomial in the elements of Ω_{d} using stochastic function approximation techniques. Modern machine learning techniques such as the Lasso (Tibshirani 1996) or Random Forests (Breiman 2001) could be employed for this task. This function $f(\Omega_{\mathrm{d}})$ could be estimated for each market participant in the control area using a large sample of data from the operation of the wholesale market.

Given estimates of $f_j(\Omega_{\mathrm{d}})$ for each firm j with the ability to exercise unilateral market power in the wholesale market during any hour of the year, implement the proposed transmission upgrade and compute new values of θ_{dj} for strategic market participant j using this function. Using the estimated functions $f_j(.)$ for each strategic player, compute $f_j(\Omega_{\mathrm{d}}(\text{proposed}))$, where $\Omega_{\mathrm{d}}(\text{proposed})$ is the value of Ω_{d} with the transmission capacity after the proposed upgrade is in place. Then feed the values of θ_{dj} for all strategic market participants implied by $\Omega_{\mathrm{d}}(\text{proposed})$ into the market model to compute new market-clearing prices and quantities. This yields the counter-factual market outcomes to compare to the baseline market outcomes without the transmission upgrade. To get baseline market outcomes, for system conditions Ω_{d}, compute $f_j(\Omega_d(\text{actual}))$, where $\Omega_d(\text{actual})$ is the value of Ω_d with the transmission capacity before the proposed upgrade.

To account for the uncertainty in future load growth, low water conditions, input fuel prices, the entry of new generation, and other elements of Ω_d, an estimate of the joint distribution of the elements is necessary. Given this distribution, values of $f_j(\Omega_s(\text{proposed}))$ and $f_j(\Omega_s(\text{actual}))$ can be computed for each strategic market participant for each draw of the vector of future system conditions, Ω_s, from this distribution. The realized values of market outcomes can then be computed for both the proposed and actual configuration of the transmission grid in the future for each of these realizations of Ω_s.

Let $M(\Omega_s(\text{proposed}))$ equal the vector of market outcomes—locational prices and production levels and demands—for future system conditions realization Ω_s with the proposed upgrade in place and $M(\Omega_s(\text{actual}))$ equal the vector of market outcomes for these future system conditions without the upgrade. Let $B(M(\Omega_s(\text{proposed})), M(\Omega_s(\text{actual})))$ be the function that maps these two vectors of market outcomes into a measure of the economic benefits of the upgrade for future system condition Ω_s.

This process gives rise to a distribution of economic benefits of the upgrade driven by future system conditions and the predictive relationship between system conditions and offers submitted by suppliers based on historical data. This approach to assessing the benefits of transmission expansion in a wholesale market regime has been applied to the California ISO's proposed Path 26 upgrade, in Awad et al. (2010). An important outcome of this analysis is an estimate of the distribution of future economic benefits of the upgrade. Although the expected value of these future benefits exceeds the expected cost of the project, the distribution of the benefits is very positively skewed, indicating the realized benefits of the upgrade can be extremely large under certain future system conditions. The mapping from system conditions to benefits, $B(M(\Omega_s(\text{proposed})), M(\Omega_s(\text{actual})))$, provides valuable information to the decision-makers because it identifies what values of the elements of the vector of future system condition, Ω_s, yield large realized benefits from the upgrade.

Another important outcome from the Awad et al. (2010) analysis is that although the upgrade under consideration allowed more presumably low-cost generation to serve load in Southern California, the major source of economic benefits from the upgrade was the reduction in the amount of the unilateral market power that was exercised as a result of the transmission network expansion. Suppliers near the major population centers in Southern California would face greater competition as a result of the upgrade because $f_j(\Omega_s(\text{proposed}))$ predicted values for the offers of local strategic suppliers closer to their marginal costs, which led to lower prices in that region.

Wolak (2015) applies a version of this methodology to assess the competitiveness benefits of the transmission expansion policy that exists in the Alberta wholesale electricity market. This analysis also found that the reduction in the ability of strategic suppliers to exercise unilateral market power was the source of the vast majority of the economic benefits associated with eliminating transmission congestion in the

Alberta market. The expected economic benefits associated with Alberta's transmission expansion policy were also found to be significantly larger with a larger share of intermittent wind generation in the system.

Hesamzedeh et al. (2010a, b) formulate an economic model to quantify how transmission network changes impact the ability of strategic suppliers to exercise unilateral market power. Hesaamzedeh et al. (2010c) construct an equilibrium model of competition between strategic generation unit owners and use it to quantify both the economic efficiency improvements and the competitiveness benefits of transmission expansions. The authors simplify the process of computing equilibrium outcomes with and without the transmission upgrade by restricting the strategic players to a finite number of actions. They employ the extremal-Nash equilibrium concept of Hesamzedeh and Bigger (2012) to compute the equilibrium with and without the transmission upgrade equilibria because their game typically has many Nash equilibria. Hesamzadeh et al. (2011) extend the authors' earlier transmission expansion modeling framework to account for the fact that expansions also allow the deferral generation capacity investments because more energy from distant locations can be used to serve demand. Their model decomposes the economic benefits of transmission expansions into efficiency benefits (lower dispatch costs), competitiveness benefits (more competitive behavior by suppliers), and deferral benefits (deferral of generation capacity investments).

These analyses emphasize the importance of accounting for the competitiveness benefits in measuring the economic benefits of transmission expansions in the wholesale market regime. Many consumer welfare-improving expansions for the wholesale market regime are likely to fail the traditional dispatch cost reduction test used in the former vertically-monopoly regime, which implies that consumers are ultimately paying more electricity than necessary. Consequently, in order for consumers to realize the full economic benefits of the electricity industry restructuring the transmission planning process must recognize this new source of economic benefits from transmission capacity in the wholesale market regime.

5.3 Implementing a Forward-Looking Transmission Planning Process

A credible estimate of the distribution of realized economic benefits from a transmission expansion requires credible estimates of the joint distribution of future system conditions. Estimates of the joint distribution of future demand conditions, input fossil fuel prices, hydrological conditions, and new generation capacity entry decisions and locations are essential to providing a forward-looking assessment of the distribution of economic benefits of a transmission expansion. Under certain realizations of future system conditions, a proposed upgrade may have very small economic benefits, but for other realizations, it may have very large economic benefits, so it is important to know the probabilities associated with each of these outcomes.

Unfortunately, it is extremely difficult, if not impossible to obtain an estimate of the joint distribution of all of the elements of vector of future system conditions, including future generation entry decisions. At best it is possible to estimate marginal distributions of these magnitudes. For example, historical data could be used to simulate the marginal distributions of future load growth, future hydrological conditions, or future input fossil fuel prices. However, as the dimension of the vector of future system conditions grows, estimating its joint distribution becomes increasingly challenging.

One approach to addressing this problem is to use information on the marginal distribution of each dimension of the vector of future system conditions to constrain the unknown joint distribution of future system conditions. Consider the following example. Suppose the vector of future system conditions Ω has three dimensions. Let the unknown joint probability that Ω takes on the specific value Ω_{ijk}, equal ρ_{ijk}. Suppose there are I realizations of the first dimension, J realizations of the second dimension, and K realizations of the third dimension of Ω_{ijk} and the marginal probabilities of each realization of each dimension are known. By the properties of joint and marginal probabilities, the following equalities hold:

$$\rho_i = \sum_{j=1}^{J}\sum_{k=1}^{K}\rho_{ijk} \text{ for } i = 1, 2, \ldots, I, \quad \rho_j = \sum_{i=1}^{I}\sum_{k=1}^{K}\rho_{ijk}\text{for } j = 1, 2, \ldots, J$$

$$\rho_k = \sum_{i=1}^{I}\sum_{j=1}^{J}\rho_{ijk} \text{ for } k = 1, 2, \ldots, K \text{ and } 1 = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\rho_{ijk}$$

The realized value of the benefits of the upgrade could be computed for each value Ω_{ijk} for all possible values i, j, and k. The analyst could then compute the distribution of realized economic benefits from the upgrade by choosing the unknown elements of ρ_{ijk} to maximize the expected value of the upgrade subject to the four sets of linear constraints given above for the known marginal distributions, $\rho_i (i = 1, 2, \ldots, I)$, ρ_j $(j = 1, 2, \ldots, J)$, and $\rho_k (k = 1, 2, \ldots, K)$, of each element of the vector of future system conditions. The same joint density could be computed for the ρ_{ijk} that minimizes the expected value of the distribution of economic benefits. These two estimated distributions of the future economic benefits provide the regulatory process with valuable information about what specific realizations of Ω_{ijk} and the associated value of ρ_{ijk} lead to the extreme high and low realizations of the future economic benefits from the upgrade. For an illustration of this approach applied to a transmission upgrade in the California ISO control area, see Awad et al. (2010).

Hesamzedeh et al. (2010a, b) formulate the transmission network expansion problem as a single leader and multiple follower game between the single transmission planner and multiple strategic generation unit owners. The transmission network owner explicitly recognizes the strategic use of the transmission network configuration by generation unit owners to maximize the profits earned in the short-term energy market. Hesamzedeh and Yazdani (2014) formulate this leader–follower game between the transmission planner and generation unit owners with the short-term energy market between quantity-setting generation unit owners. Tohidi et al. (2017b) extend this leader–follower approach to modeling transmission network expansions to account for both the strategic entry and operating decisions of generation unit owners. Because the configuration of the transmission network impacts generation unit entry decisions, Tohidi et al. (2017a) attempt to achieve more efficient transmission and generation expansion in the wholesale market regime through the use of locational transmission network changes. These charges capture the impact of incremental generation unit investments on transmission network costs.

All of these forward-looking approaches to modeling transmission network expansions described above explicitly account for the expected profit-maximizing strategic response of generation unit entry and operating decisions in the transmission planning process in order to maximize the economic benefits consumer receive from transmission expansions in the wholesale market regime.

5.4 Modeling Policy-Driven Future Entry Decisions

Renewable energy goals are likely to be achieved at significantly lower costs to consumers with a forward-looking transmission planning process. One element of the vector of future system conditions could be the extent and rate at which renewable energy goals are met. For example, if a region has aggressive renewable energy goals and a marginal probability distribution associated with these goals being met, under the realizations where these goals are met, the benefits of a substantial transmission expansion into a region with rich renewable resources could have substantial realized economic benefits. An expansion policy that is not forward-looking might instead choose a smaller expansion that subsequently forecloses significant new generation investments into this region because of the high cost of adding incremental transmission capacity into this region.

A forward-looking transmission expansion policy is also the least-cost way to ensure that renewable energy can compete to be part of the total generation mix. The cost of the transmission interconnection facilities for the typical wind or solar project is a much larger fraction of the cost of constructing the generation facility because these generation units tend to be located far from major load centers. In addition, because there are likely to be many individual renewable generation projects at a single remote location, the size of the interconnection facility needed to serve all of these projects is substantially larger than the interconnection facility needed to serve any single renewable resource project at that location. For example, a location may have the potential to support 1000 MW of wind resources, but the average size of the wind projects at this location may be 100 MW. Because of economies to scale in constructing transmission interconnection facilities, it may be much cheaper from a discounted present value of the dollar per MW cost perspective to construct interconnection facilities with the capacity to serve the 1000 MW wind generation potential that exists at this location rather than builds only the capacity needed to serve the initial 100 MW project and then add more interconnection capacity as more wind generation capacity enters at this location.

If the costs of coordinating all of the expected renewable resource suppliers at a remote location in order to construct the single large interconnection facility are sufficiently high, then renewable resources owners may instead choose to construct these interconnection facilities sequentially as each new facility begins producing. This sequential construction of the necessary interconnection facilities will result in a total cost for interconnecting all of the eventual renewable suppliers at that location that is larger than the cost of the single interconnection facility built to serve all of these suppliers at the time the first supplier begins producing. However, if the total costs of such a large interconnection facility were charged to the first entrant, it may be so high as to prevent development at all. A forward-looking transmission policy will ensure that positive net benefit facilities will be constructed despite the fact that no individual renewable electricity supplier would find unilaterally profit-maximizing to construct it.

Finally, because the entry decisions of suppliers, the ability of suppliers to exercise unilateral market power as well as uncertainty in future system conditions and future input fuel prices, demand growth, hydrological conditions, and future renewable energy goals impact the realized economic benefits of a transmission expansion, the traditional small-number-of-future-scenarios approach to quantifying benefits of transmission upgrades is likely to provide a very incomplete estimate of the distribution of future benefits. A full characterization of the distribution of future realized benefits is likely to lead to more informed transmission planning decisions.

6 Increased Sophistication of Transmission Planning Process

As should be clear from the previous sections, the sophistication of the economic modeling required to assess the benefits of transmission expansions in the wholesale market regime is much greater than that required for the vertically-integrated regime. In the vertically-integrated regime, there no need to model the strategic response of electricity suppliers to the transmission network expansion. There is also no need to account for strategic entry and exit decisions and locations of generation units in response to network expansion. Finally, there is no need to model the strategic response of suppliers to load growth, input fuel prices, hydrological conditions, and other future system conditions.

6.1 The Downside of Open Access

The need for a sophisticated transmission planning process is greater in the wholesale market regime because no single entity has a financial interest in finding the least-cost combination of transmission and generation capacity to meet load throughout the entire wholesale market.[8] Under the vertically-integrated monopoly regime, the monopolist had little incentive to take actions to increase the total cost of meeting its load obligation by operating expensive local generation units because it had a legal obligation to serve all demand in its service territory at a regulated retail price. The combination of a fixed retail price and the obligation to serve all demand at that price gave the vertically-integrated monopolist a strong incentive to find the least-cost mix of generation and transmission investments to meet these load obligations and a strong incentive to operate its fleet of generation units in a least-cost manner.

As discussed above, in the wholesale market regime, a generation unit owner that faces insufficient competition from other suppliers has an incentive to take advantage of its location in the transmission network to increase the price that it is paid to supply electricity by changing its offer price or the amount of energy it makes available to the short-term market. Moreover, a supplier may also have an incentive to construct new generation capacity in locations where it can take advantage of its favorable location in the transmission network to raise wholesale prices through its offer price and capacity availability decisions. All of these factors imply significant benefits to consumers from a transmission policy that attempts to find the "optimal second-best" configuration of the transmission network.

6.2 The Form of Congestion Management Matters for Benefits Measurement

The specific mechanism used to manage and price transmission congestion must be modeled in order to determine the economic benefits of transmission expansions in the wholesale market regime. That is because how congestion is managed and priced impacts how suppliers behave in the wholesale market regime and ultimately market-clearing prices and the amount consumers pay for wholesale electricity. For example, offers that are expected profit-maximizing for suppliers in a single-zone or multi-zone market may no longer be expected profit-maximizing in the LMP market design. Performing an assessment of the economic benefits of a transmission expansion using an LMP market design when the actual market sets a single market-wide price or prices in a small number of zones is likely to lead to extremely inaccurate estimates of the economic benefits on an upgrade. For example, Bushnell, Hobbs,

[8] In the United States markets the Independent System Operator (ISO) is only charged with operating the transmission network, although it is a major participant in the transmission planning process. United States ISOs are non-profit entities that do not receive a direct financial benefit from finding the least-cost mix of transmission and generation capacity.

and Wolak (2008a) note how to offer behavior in the California ISO's zonal market would change as a result of the shift to an LMP market design from zonal market design.

This logic implies that different congestion management mechanisms are likely to have different "optimal second-best" amounts of transmission capacity. For example, a single zonal price model implicitly assumes that all generation units in the control area are able to compete against each other to supply electricity during all hours of the year. This logic implies that optimal amount of transmission capacity for a single-zone market is likely to larger than the optimal amount of transmission capacity for a multi-zone market that only assumes that all generation units in each zone are able to compete against each other to supply electricity during all hours of the year.[9]

Even the local market power mitigation employed for the same market design will impact the "optimal second-best" transmission capacity. There is some degree of substitutability between the stringency of the market power mitigation mechanism and transmission expansions in limiting the ability and incentive of suppliers to exercise unilateral market power. Consequently, the distribution of economic benefits of a given transmission upgrade will also depend on the form of the local market power mitigation mechanism employed.

6.3 Expanded Geographic and Industry Scope

The geographic scope of the planning process is another dimension along which the sophistication of the process should increase relative to the vertically-integrated monopoly regime. Because most formal wholesale electricity markets were formed from joining the service territories of multiple vertically-integrated utilities, the geographic scope of the transmission planning process must expand to account for this fact. Because of the looped nature of many transmission networks, expanding capacity in one geographic area can significantly alter the available transmission capacity in other geographic regions. The benefits and costs of an upgrade should, therefore, be accounted for in the transmission planning and expansion process for the entire region.

In the former vertically-integrated monopoly regime, regulators typically only counted benefits from a transmission expansion that accrued to the utility undertaking the expansion. If an expansion by one utility benefitted a neighboring utility, these economic benefits were not typically counted in the transmission planning process for that utility. While there may have been some logic to this approach to benefits assessment in the vertically-integrated monopoly regime, this approach makes very little sense in the wholesale market regime.

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[9]A major reason for the abandonment of zonal market designs in all wholesale markets in the United States and the increasing challenges faced by zonal markets in Europe is the failure of the transmission planning and expansion process to make these implicit assumptions into reality through forward-looking transmission expansions.

There is even an argument for expanding this economic benefits calculation to include neighboring control areas, assuming there is a way for the region undertaking the investment to capture these economic benefits. This could be possible through some cost-sharing agreement with the neighboring control area negotiated before the upgrade takes place. Tohidi and Hesamzedeh (2014) model multi-regional transmission planning as a non-cooperative game between neighboring control areas that only care about the economic surplus in their control area versus a cooperative regional transmission planning process where the planner cares about the total economic surplus in both areas. The authors use their modeling results to argue that there are significant economic benefits from regional coordination of transmission planning processes. Tohida et al. (2018) employ a modified Benders decomposition to solve this game incorporating a transmission network investment risk based on the probability of a supply shortfall.

By the same logic that transmission network expansions enhance the competitiveness of wholesale electricity markets, natural gas transmission and distribution network expansions can enhance the competitiveness of wholesale natural gas and electricity markets. If expanding a gas transmission line reduces the frequency of gas curtailments and short-term natural gas price spikes, this will provide lower and less volatile natural gas prices to electricity generation unit owners, which should, in turn, increase the extent of competition to supply electricity.

Expanding natural gas pipeline capacity near locations with significant interconnection capacity for new natural gas-fired generation capacity will facilitate new entry of generation capacity and increase the competitiveness of the wholesale electricity market. For these reasons, there is a clear consumer benefit in terms of protecting consumers from the exercise of unilateral market power in the natural gas and wholesale electricity market from coordinating the natural gas and electricity transmission planning process.

An additional source of economic benefits from coordinating these two planning processes arises in wholesale markets with significant renewable energy goals. The cost of storing renewable electricity as hydrogen or natural gas is facilitated by the proximity of renewable generation capacity to the natural gas network. This will reduce the cost of injecting hydrogen or natural gas produced from renewable energy into the natural gas network.

6.4 The Viability of Market-Based Transmission Expansions

A distinguishing feature of a looped transmission network is that expanding one link can provide economic benefits to users of virtually all of the links in the transmission network. For this reason, it is generally impossible for the entity undertaking a transmission upgrade to capture all or even a significant fraction of the benefits of that upgrade. This logic has important implications for market-based mechanisms for funding transmission expansions. Specifically, relying on the revenues earned from locational price differences to fund transmission expansions is likely to lead to very limited transmission expansions and high levels of congestion in the transmission network.

One approach that has been proposed to fund transmission expansions is what has been called the "merchant transmission model" where an investor constructs a transmission line in exchange for the receiving the difference between the prices at the source and the sink of the transmission link times the capacity of the transmission line each trading period.[10] For example, if the price at the sink of the transmission line is \$80/MWh and the price at the source is \$50/MWh, then the owner would receive \$30/MWh times the capacity of the transmission link. The merchant transmission model assumes that these locational price differences provide the economic signals necessary for fund transmission expansions.

There is virtually no empirical evidence to support the viability of the merchant transmission model, except in very rare circumstances.[11] As Joskow (2019) notes, competition to supply transmission capacity typically takes place after the regulatory process has decided to undertake a transmission expansion project. Because the locational price difference between two points in the transmission network typically captures a small portion of the benefits of the transmission upgrade, there have been few, if any, financially viable merchant transmission projects in any wholesale market. Virtually all transmission expansions are the result of a formal transmission planning process and are funded through a single system-wide transmission tariff.

7 The Insurance Value of Transmission Expansions

Future system conditions are the major driver of the realized benefits of any transmission upgrade. There are many sources of uncertainty that impact future system conditions. Market prices depend on many unknown factors such as input fossil fuel prices, the amount of entry by new generation unit owners, the level of load growth, and the outages of generation units and transmission facilities. In hydroelectric-dominated systems, water levels are a crucial determinant of wholesale electricity prices. Another source of short-term price uncertainty is the amount of fixed-price forward market obligations sold by suppliers. To compute an accurate estimate of the expected benefits of a proposed upgrade, the analyst must account for the full range of uncertainty in each of these dimensions of future system conditions. Otherwise, the expected benefits of a transmission upgrade under the wholesale market regime will be dramatically underestimated. This logic also emphasizes that transmission upgrades have a substantial insurance value, particularly under the wholesale market regime.

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[10] Joskow (2019) discusses the economic viability of this merchant transmission investment model.

[11] The few examples of viable merchant transmission projects are direct current (DC) lines from a remote location to a generation load pocket, rather than upgrading or building a link in a looped alternating current (AC) high voltage network.

Transmission upgrades can significantly reduce the likelihood of system conditions that produce extreme prices. For example, large interconnections between California and neighboring control areas can substantially reduce the probability of extreme prices in California. For example, if a temporary shortfall in natural gas availability in California causes electricity prices to rise significantly, a large interconnection with the Pacific Northwest allows hydroelectric energy to substitute for expensive natural gas-fired electricity. A large interconnection with the Desert Southwest could allow coal-fired energy to displace expensive natural gas-fired energy in California. Under normal conditions for natural gas availability in California, this interconnection may not be fully utilized, but it does provide insurance against this and other potential supply uncertainties within the state.

Because the impact of physical constraints on system conditions are often exacerbated by the strategic behavior of suppliers, the insurance value of transmission expansions is likely to be even larger under the wholesale market regime than under the vertically-integrated monopoly regime. For example, there are many examples of from hydroelectric-dominated wholesale markets around the world of fossil fuel suppliers taking advantage of low water conditions and submitting much higher offer prices because they know that hydroelectric suppliers must conserve water rather than compete vigorously to supply electricity to the short-term market.[12] Similar logic applies in a natural-gas-dominated market such as California. If the price of natural gas rises substantially, then out-of-state coal-fired generation unit owners could submit higher offer prices because they face less competition at their former offer prices from the natural gas-fired generation unit owners. However, if there is substantial interconnection capacity with neighboring control areas, the coal-fired suppliers will still face competition from coal-fired suppliers in other control areas and will be unable to raise wholesale prices in California.

The events of June 2000 to June 2001 in the California electricity market provide a vivid illustration of the extent to which extreme events can drive the benefits of a transmission expansion.[13] Specifically, had there been significant transmission capacity available to transfer electricity from the Eastern Interconnection to the Western Interconnection, it is unlikely that the enormous increase in electricity prices in the Western US would have occurred during this time period. This transmission capacity could have allowed consumers in the Western US to avoid paying prices that were orders of magnitude higher than prices in the Eastern US during this time period. In addition, this interconnection would have also eliminated the need for the State of California to sign long-term forward contracts during the winter of 2001 at prices more than double wholesale prices during first two years of operation of the California market in order to commit suppliers to the California market during the summer of 2001 onwards. A very conservative estimate of the realized discounted present value of the benefits of this interconnection to consumers in the

[12] Wolak (2009) describes the case of New Zealand and McRae and Wolak (2016) the case of Colombia.

[13] Wolak (2003a) provides a diagnosis of the causes and consequences of the California electricity crisis and Borenstein et al. (2002) assess its economic efficiency consequences.

Western US (because it would have prevented the events of June 2000 to June 2001 from occurring in the Western US) is on the order of 30 billion dollars.[14]

The substantial economic harm caused by a sustained period of extreme wholesale electricity prices argues in favor of incorporating some degree of risk aversion into the process used to assess the distribution of net benefits from a transmission expansion. For example, electricity consumers are likely to prefer a transmission expansion project that has produces market outcomes with a certain \$1 million net benefit relative to a competing reliability project that has a −\$100 million net benefit and a \$102 million net benefit each with equal probability, despite the fact that both projects have the same expected net benefit. A transmission expansion project that increases the number of distant suppliers that can sell energy into the market has a much more certain net benefit distribution than a demand response or local generation project that does not increase the number of new suppliers able to sell energy into the wholesale market. Consequently, if risk aversion is an important concern, then the transmission planning process should guard against under-investment in the transmission network rather than over-investment in the transmission network.

Over-investment (relative to an expected net economic benefit criterion) in the transmission network protects against rare, but extremely costly market outcomes. Specifically, even though consumers will be asked to pay for more transmission capacity in all future states of the world, the upgrade will eliminate the realization of a market outcome that is extremely costly to consumers. Under-investment in the transmission network subjects consumers to the prospect of extremely costly market outcomes in exchange for slightly lower transmission charges in all states of the world. If consumers are risk-averse then they should prefer an outcome that slightly over-invests in transmission capacity relative to one that slightly under-invests in transmission capacity, even if consumers expect to pay the same price for retail electricity under both scenarios.

The argument for a transmission planning process that treats over-investment in the transmission network as less harmful to consumers than the under-investment is strengthened by the fact that less than 10% of the average retail price of electricity in most jurisdictions pays for the transmission network. This percentage is unlikely to increase because of expectations of increasing fossil fuel prices and a positive price for greenhouse gas emissions. These two factors imply that consumers can realize even greater economic benefits from a wholesale electricity market that faces all suppliers with the maximum amount of competition and allows consumers to have access to the lowest-cost sources of electricity for as many hours of the year as possible. This set of circumstances can only exist if there is a forward-looking transmission policy that plans, sites, and builds transmission facilities in anticipation of generation unit entry and operating decisions.

[14] Wolak et al. (2004) provide this conservative estimate of the cost of the California electricity crisis.

8 Conclusion

The current regulatory structure in the United States governing transmission planning and expansions is poorly suited to the wholesale market regime that serves the vast majority of electricity consumers in the United States. The foregone benefits to United States electricity consumers associated with the current regulatory framework governing transmission planning and expansions are substantial and are very likely to become much larger as the electricity supply industry transitions to low-carbon energy sources. A coordinated transmission planning and expansion process tailored to the wholesale market regime can significantly increase the economic benefits electricity consumers realize from all money spent on transmission expansions and substantially increase the rate at which low-carbon electricity sources are able to interconnection and sell electricity to final consumers and the ultimate benefits realized from electricity industry restructuring.

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