A Joint Energy And Transmission Rights Auction: Proposal and Properties

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***Abstract*— An auction-based process is proposed that allows power market participants to acquire and reconfigure financial transmission rights. The process simultaneously accommodates flowgate and point-to-point options and obligations, along with energy production and consumption futures. A sequence of auctions is held during which participants can buy and sell rights, culminating in a real-time auction, at which time all rights are cashed out. By allowing flowgate and point-to-point obligations and options to be reconfigured and exchanged, the market can decide what combination of financial rights are most useful to power generators, consumers, and traders. Rights can be exchanged not only for capacity of individual flowgates, but also for more complex transmission constraints, such as nomograms. Under certain conditions, we prove that the auction is revenue adequate for the market operator, in that payments to rights holders cannot exceed congestion revenues. We present a linearized (DC) auction along with a numerical illustration.**

***Index Terms*—Transmission rights, Regional Transmission Organizations, markets, deregulation, optimization.**

I. INTRODUCTION

Efficient congestion management and tradable transmission rights are fundamental elements in the design of restructured power markets. This issue is central in the US debate over market design for regional transmission organizations (RTOs). RTOs are envisioned as the next step in open transmission access [9,10]. One aim of the RTO initiative is to overcome the balkanization of US wholesale energy markets by defining transmission pricing schemes with a broad geographical scope. The balkanization issue is also crucial in the European Union [2,12,16].

Most observers are now aware of the advantages for efficient congestion management of locational marginal pricing (LMP) of energy, also called nodal pricing [13,22]. In LMP, the spot price at each bus on the network reflects the marginal cost of energy at that time and location, accounting for losses along with out-of-merit-order dispatch caused by transmission congestion. The transmission cost equals the difference between nodal prices at the points of withdrawal and injection.

While there is growing appreciation of LMP, there is still significant disagreement over the appropriate method for specifying transmission rights so that scarce transmission capacity can be allocated and market participants can hedge congestion costs [27]. The disagreements concern the two basic types of financial transmission rights currently being discussed: the point-to-point right [4,13] and the flow-based right [6,7,23]. Advocates of these types of rights often present them as mutually exclusive, highlighting the advantages of one type and disadvantages of the other.

The basic point-to-point financial right (also called a "firm transmission right", or FTR) requires its owner to collect from the RTO an amount equal to the MWh quantity of the right times the difference in nodal prices (in \$/MWh) between two specified nodes. (Thus, strictly speaking, this is really a contract or obligation rather than a right; however, we refer to it as a transmission "right", consistent with the literature.) Such rights are used in northeastern US markets. Point-to-point rights are well-suited for hedging congestion costs for longer-term transactions involving known injection and withdrawal points. Under certain conditions, as long as the flows implied by the issued point-to-point rights are simultaneously feasible for the network, the RTO's payments to rights holders are guaranteed to be no more than the RTO's congestion income from users of the network [13].

However, a disadvantage of the point-to-point financial right, from the perspective of market traders, is the large number of potential point-to-point combinations. Resellers of such contracts face thin or nonexistent markets for rights for specified pairs of points. Further, any change in configuration of a particular right requires that simultaneous feasibility be maintained with all other outstanding rights. Such problems limit development of off-RTO secondary markets [24].

This lack of flexibility worries participants in forward markets who want to change points of injection and withdrawal frequently as they adjust their portfolios to reflect changing market opportunities. The flow-based rights approach addresses this concern. It builds point-to-point rights or rights between aggregations of points (*e.g.,* zones or hubs) by combining rights to flows through individual flowgates that can then be rebundled and traded as desired. Market participants can tailor the bundle of rights to their needs. Electricity traders often argue that because there will be fewer

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congested flowgates to hedge than the hundreds or thousands of node combinations in regional electricity markets, flow-based rights will yield a more liquid forward market for energy and transmission. Another advantage may be that flowgate pricing gives explicit incentives to invest in transmission capacity, as it associates payments with particular facilities.

Criticisms of the flow-based model focus on assumptions of the number of the set of significant flowgates and their stability [4,14,21]. For instance, consideration of multiple contingencies or of flowgates involving jointly determined flow limits (such as nomograms) can dramatically increase the number of flowgates needed to support a particular energy transaction. Critics thus argue that these rights will be no simpler in practice than point-to-point contracts, and perhaps more complex. Ref. [7] replies to these criticisms.

This paper proposes that the RTO provide both types of rights simultaneously as either options or obligations, settle all transmission rights at locational prices, and avoid subsidizing rights holders. The market is then allowed to decide what mix of types of rights is best. Proposals made elsewhere include elements of this idea [14,15,24]; the idea also underlies the Midwest RTO now under discussion [17], and is cited favorably by experts testifying before FERC [10]. Ref. [1] shows the essential equivalence of point-to-point and flow-based systems assuming perfect competition and that all flowgates are traded for all contingencies.

Our paper makes two contributions to this literature. First, we propose that the RTO operate a "joint energy and transmission rights auction" (JETRA). JETRA would encompass both forward and dispatch markets for energy and transmission. Both point-to-point and flowgate rights are exchanged in JETRA (unlike [14,15], in which the RTO auctions one type of right and accommodates off-RTO trading in the other type). Second, we provide a rigorous basis for offering point-to-point options as well as obligations and flowgate rights while ensuring revenue adequacy, meaning that the RTO will not have to make up revenue shortfalls by charging transmission users “uplift” costs. JETRA can also include unbalanced point-to-point obligations [11] and other electricity services, such as installed capacity or operating reserves.

JETRA is a trading system that ensures physical reliability and financial feasibility of executed trades. JETRA allows parties who desire to buy or sell financial rights to bid for their preferred mix of point-to-point and flow-based rights and energy forwards, and then modify their holdings through subsequent iterations of the auction or through bilateral transactions. Except for the final iteration, JETRA is a linear or nonlinear program that allocates financial rights for point-to-point transactions and flowgate rights to the highest bidder, while maintaining revenue adequacy. In the last iteration (real-time dispatch), prices for transmission services of both types are determined by the LMP approach.

The next section describes some general features of the auction. Section III then presents a linear-programming implementation of JETRA based upon a DC load flow approximation [3,22]. That section also describes how point-to-point options are modeled. Financial settlement procedures are presented in Section IV, as is a proof of revenue adequacy. We close with a numerical example and conclusions.

II. FEATURES OF THE JOINT AUCTION

The JETRA model and procedures reflect the experience of the PJM and New York markets. These markets have:

- an integrated energy and transmission market (operated as day-ahead and real-time markets in the Northeast),
- voluntary choice by market participants as to whether to transact outside the RTO electricity product markets (through self-scheduling, bilateral contracts, or schedule coordinators) or to bid into the RTO markets,
- LMP-based congestion management, and
- financial point-to-point transmission rights.

A difference between JETRA and these markets is that JETRA adds liquidity to bilateral markets by adding user-defined flow-based rights. We also propose more general point-to-point rights, including options, unbalanced obligations, and multiple-point-to-multiple-point rights. Market participants therefore have the flexibility to develop and redefine hedging instruments to fit their needs.

A. Rules for Energy Trading

The JETRA rules for energy trading are general and unrestrictive. Market participants can transact voluntarily through the centralized RTO market, through bilateral transactions, or via multilateral power exchanges (operating as schedule coordinators) separate from the RTO. Or they can create self-schedules, which are requests to the RTO to turn on a generator for a period of time as a price taker in the spot energy market. The joint auction can then operate day-ahead for energy and congestion bids (and for exercise of transmission rights) and hourly for real-time energy sales, like the systems implemented in PJM and some other markets.

Unlike present market designs in the US, forward energy commitments will be allowed before day-ahead markets. In some cases, such forward commitments are used to ensure that transmission capacity is available for forward sale, that is, allowing some generators to offer both energy and transmission. For example, the physical characteristics of the San Francisco Bay area grid (like some other electrically isolated areas) require that local generators operate to allow for additional transmission into the area. (We discuss this example further in Section III.) JETRA accommodates this and similar interdependencies between energy and transmission, assuming that locational market power concerns are addressed.

B. Rules for Point-to-Point and Network Transmission Rights

The JETRA rules for point-to-point transmission rights or rights encompassing multiple points follow the basic format of the existing auctions in PJM and New York. The primary auction for reconfiguring rights is offered monthly or possibly more often. A secondary market can operate continuously and separately from JETRA. Point-to-point rights can either be carried or cashed out in a forward market, or eventually settled in the real-time spot market. Alternatively, the final auction used to settle rights could be a day-ahead auction, with a separate balancing mechanism to handle real-time dispatch.

C. Rules for Flow-Based Transmission Rights.

Like point-to-point rights, flow-based rights are financial rights and thus do not affect the physical dispatch. The JETRA procedures for flow-based rights are as follows:

1. Periodically, the RTO makes available a full network model including all transmission constraints and a set of historic power transmission distribution factors (PTDFs), or sets of PTDFs based on contingencies.
2. Market participants (or the RTO) calculate the flowgate capacity required by their transactions and develop a bid strategy (bid price, quantity required, period required) that covers some or all of the flowgates.
3. JETRA market participants trade (buy and sell) flow-based rights simultaneously with point-to-point obligations and options.
4. Finally, in the real-time or dispatch auction, all transmission users are charged the locational marginal congestion costs associated with their transactions. Holders of flow-based rights are paid the price (dual variable) of their flowgates times the quantity of their rights.

III. JETRA: THE LINEARIZED DC CASE

For simplicity, we focus here on a linearized DC version of JETRA to illustrate a few basic points. More general nonlinear versions are analyzed in [18]. The statement below of JETRA is simplified in many ways to make the structure of the market clear. In real use, JETRA would be expanded to include crucial technical considerations such as ancillary services (which, in the case of operating reserves, can also be let for bid), must-run generators, and market power mitigation.

A. Mathematical Statement

An implementation of JETRA for a forward market using a lossless DC load flow approximation can be stated as: Maximize the value of accepted bids for point-to-point and flowgate rights and for forward energy commitments, subject to (linearized) transmission constraints. In real-time, where transmission bids are excluded, JETRA is instead: Maximize the bid value of energy consumption net of generation bid costs, subject to scheduled bilateral transactions. JETRA thus generalizes optimal dispatch models to include transmission rights [19]. Phrased mathematically, we have:

$$\textbf{JETRA: } \text{MAX } \boldsymbol{b_1 t_1} + \boldsymbol{b_2 t_2} + \boldsymbol{b_3 t_3} + \boldsymbol{b_g g} \qquad (1)$$

$$\text{subject to: } \boldsymbol{\beta_1 t_1} + \boldsymbol{\beta_2 t_2} + \boldsymbol{\beta_3 t_3} + \boldsymbol{\beta_g g} \le \boldsymbol{F} \qquad (\mu) \qquad (2)$$

$$\boldsymbol{\alpha_2 t_2} + \boldsymbol{\iota g} = 0 \qquad (\lambda) \qquad (3)$$

$$\boldsymbol{T_{Lp}} \le \boldsymbol{t_p} \le \boldsymbol{T_{Up}},\ p=1,2,3;\ \ \boldsymbol{G_L} \le \boldsymbol{g} \le \boldsymbol{G_U}. \qquad (4)$$

The objective (1) is the bid value of the accepted contracts. Eq. (2) is the transmission constraint, while (3) requires that energy provided equals energy supplied. The dual variables for these constraints, which are used in financial settlement, are shown next to the constraints. The last set of constraints (4) consists of bidder-specified upper bounds. The notation is as follows (bolded symbols indicate vectors):

$\boldsymbol{t_1}$: A column vector of *flow-based* financial transmission *options* awarded to bidders. Each element t_{1i} represents a distinct bid i by a bidder for rights to revenue from one or a portfolio of transmission constraints. (A single bidder can submit multiple bids i for different constraints, or for various amounts of the same constraint.) Bidders state the lowest and highest amount of the rights that they wish to buy or sell as $\boldsymbol{T_{L1}} = \{T_{L1i}\}$ and $\boldsymbol{T_{U1}} = \{T_{U1i}\}$, respectively.

$\boldsymbol{t_2}$: A column vector of *point-to-point* financial transmission *obligations* awarded to bidders. Its elements t_{2j} represent separate bids for the obligation to collect the difference in nodal prices between two points, or for more general multipoint obligations. Bidders give lower (upper) limits $\boldsymbol{T_{L2}} = \{T_{L2j}\}$ ($\boldsymbol{T_{U2}} = \{T_{U2j}\}$) to the amount of such rights. The net MW injection (summed across nodes) for bid k is $\alpha_{2j}t_{2j}$; $\boldsymbol{\alpha_2}$ is defined as the row vector $\{\alpha_{2j}\}$.

$\boldsymbol{t_3}$: A column vector of *point-to-point* financial transmission *options* awarded to bidders. Elements t_{3k} are separate bids for the option to collect the difference between the nodal prices at two points, or for general multipoint rights. Bidders provide lower (and upper) limits $\boldsymbol{T_{L3}} = \{T_{L3k}\}$ ($\boldsymbol{T_{U3}} = \{T_{U3k}\}$) for $\boldsymbol{t_3}$. Unlike point-to-point obligations, we limit options to balanced bids in order to ensure revenue adequacy; thus, no α_{3k} is necessary. (However, more general formulations may be possible.)

$\boldsymbol{g}$: A column vector (in MW) with elements g_m, $m = 1,\ldots,$M, one for each bid to buy or sell energy. The bidder's lower and upper bounds are $\boldsymbol{G_L}$ and $\boldsymbol{G_U}$, respectively.

$\boldsymbol{b_1}$, $\boldsymbol{b_2}$, $\boldsymbol{b_3}$, $\boldsymbol{b_g}$: \$/unit bids (row vectors) for flow-based rights, point-to-point obligation and option rights, and energy forwards, respectively. Negative bids are usually associated with sales of rights rather than purchases.

$\boldsymbol{\beta_1}$, $\boldsymbol{\beta_2}$, $\boldsymbol{\beta_3}$, $\boldsymbol{\beta_g}$: The amount of transmission rights consumed or (if negative) provided per unit of $\boldsymbol{t_1}$, $\boldsymbol{t_2}$, $\boldsymbol{t_3}$, and $\boldsymbol{g}$, respectively. For flow-based rights, the amount of rights to constraint h in (2) that are awarded to bid i is $\beta_{1ih}t_{1i}$; in matrix notation, the total awarded is the vector $\boldsymbol{\beta_1 t_1}$. (Negative β_{1ih} represent bids to sell additional flow-based rights, and would usually be accompanied by a negative b_{1i}.) For point-to-point rights, the induced amount of flow through transmission constraint h (usually in MW) implied by point-to-point bid k is $\beta_{2jh}t_{2j}$ (in matrix form, $\boldsymbol{\beta_2 t_2}$). For constraints involving single transmission elements (lines, transformers), the DC load flow assumption bases β_{2jh} on the PTDFs for the configuration of injection and withdrawal points for bid j. (In contrast, a flowgate $\boldsymbol{t_1}$ bidder is free to specify whatever β_{1ih} it desires.) The PTDFs can also be based on the anticipated marginal effects of transactions calculated from AC load flow models. Similarly, $\boldsymbol{\beta_g g}$ accounts for flows that energy withdrawals or injections induce through transmission elements. We defer discussion of $\boldsymbol{\beta_3 t_3}$ until Section III.C.

$\boldsymbol{F}$: A column vector of capacities of transmission flowgates $\{F_h\}$ for which financial contracts are being auctioned. For lines, these may be thermal, stability, or contingency limits. A constraint can also be associated with several physical elements, as in nomograms. $\boldsymbol{F}$ is often but not always expressed in MW. The dual variables of these constraints can be used to derive LMPs [6,13,22].

$\boldsymbol{\mu}$: A row vector of dual variables (shadow prices, usually in

$/MW), one dual for each transmission constraint. $\boldsymbol{\mu F}$ is termed the transmission surplus, and equals the marginal congestion cost in the final iteration of JETRA.

$\boldsymbol{\iota}$: A row vector of ones.

λ: The marginal cost of energy supply ($/MW) at the hub node assumed in the PTDFs.

The decision variables can be interpreted as follows. In a sense, flow-based rights $\boldsymbol{t_1}$ are purchases or sales of the "right hand sides" of the transmission constraints. For instance, if bidder i=3 offers $600 for 60 MW of flowgate h=7 and 30 MW of flowgate h=9 (which the buyer wants to purchase in the proportion 2:1), then we could represent this as $b_{1,3}$ = 10 $/MW, $T_{U1,3}$ = 60 MW, $\beta_{1,3,7}$ = 1, and $\beta_{1,3,9}$ = 0.5. Meanwhile, point-to-point obligations $\boldsymbol{t_2}$ and energy purchases/sales $\boldsymbol{g}$ use up (or add to) transmission capacity based on their PTDFs or other physical relationships. We delay the interpretation of point-to-point options until the Section III.C.

B. Examples of Complex Transmission Constraints

Most of the constraints (2) will be simple flow constraints for individual circuits or interfaces. However, some will be more complex, and we discuss three examples of such constraints below: nomograms, phase shifters, and contingencies.

Nomograms are general relationships between generation in one or more areas and power transfers. As examples, transfer capacity from B to A might depend nonlinearly upon the transfer taking place from C to A, or the ability to import power may be affected by the voltage support or counterflows provided by local generation. The San Francisco nomogram referred to earlier is an example. There, additional transmission transfer capability into that region is made feasible by the dispatch of local generation. To fit the linear programming framework, we use a piecewise linearization of the nonlinear nomogram. This yields *two* linear constraints (California ISO, personal communication):

$$\boldsymbol{\beta_{1SF(a)}}\,\boldsymbol{t_1} - INJECT_{SF} + 0.5(WITHDRAW_{SF}) \le 35\ MW \tag{5}$$

$$\boldsymbol{\beta_{1SF(b)}}\,\boldsymbol{t_1} - INJECT_{SF} + 0.7(WITHDRAW_{SF}) \le 89\ MW \tag{6}$$

where $INJECT_{SF}$ is the sum of (positive) MW injections in San Francisco by point-to-point rights and generation, and $WITHDRAW_{SF}$ is the sum of withdrawals associated with consumers and point-to-point rights. $\boldsymbol{\beta_{1SF(a)}}$ is a row vector representing the amount (per unit of $\boldsymbol{t_1}$) of the right-hand side of the first linear segment sold as flow-based financial rights, while $\boldsymbol{\beta_{1SF(b)}}$ corresponds to the sale of such rights to the second segment. The constraints show that sales of point-to-point rights involving San Francisco are treated differently by the nomogram depending on whether they are withdrawals or injections. Complex nomograms can often be approximated by linear segments in this manner. Alternatively, a nonlinear version of JETRA [18] could be used that represents the nomogram by a single nonlinear constraint.

As a second example of a more complex constraint, variables representing settings of phase shifting transformers or FACTS devices could be introduced, and constraints introduced to represent limits on their settings or flows through the devices. Ideal phase shifters are easily accommodated by the linear model (1)-(4) [25], and financial rights $\boldsymbol{t_1}$ for the limits on phase angle changes could be sold in JETRA. Note that these rights are financial rights to a constraint; the RTO retains responsibility for the physical control of the device.

The third example is contingencies. As security-constrained dispatch often limits flows so that (n-1) or higher order contingencies do not result in unacceptable overloads, such constraints should also limit transmission rights. For instance, power imports to the Netherlands and neighboring countries are limited by two contingencies each involving a particular circuit [12]. This situation could be represented in JETRA by including three sets of constraints (2) in the model, one for the case of no outage and one for each of these two (n-1) contingencies. Point-to-point and energy bids would automatically be entered in each set based on the appropriate PTDFs, while flowgate bidders would tailor their values of $\boldsymbol{\beta_1}$ to meet their needs under each contingency.

Of course, a challenge will be to identify what contingencies might realistically occur in real-time so that market participants can fully hedge their transactions and the RTO can ensure revenue adequacy. Although the problem of identifying contingencies is often phrased as a criticism of flowgate rights systems, it is also a problem for pure point-to-point systems if revenue adequacy is to be guaranteed. Another challenge is the computation of PTDFs under multiple contingencies, for which Hogan and Pope [15] offer some ideas.

C. Options vs. Obligations

The basic flow-based right is a pure right (option), and can be of two types. The simple rent collection right (positive β_{1ih}) confers the right to collect positive rents on a transmission constraint. The rent collected is never negative in that case (as the dual variables $\boldsymbol{\mu}$ for $\le$ constraints are necessarily nonnegative). In contrast, the simple rent payment "right" or contract (negative β_{1ih}) commits the seller to pay the RTO any positive rents on a constraint. These payments are, for the same reason, nonnegative. The so-called flow-based *obligation* [17] is actually a combination of these, consisting of a right to collect congestion rents on one direction on a constrained line paired with the commitment to pay rents for congestion in the other direction.

Similarly, *point-to-point obligation* rights can involve either negative or positive payments. The sign is not generally known *a priori*. This type of right (actually, a contract) is the obligation to collect or pay the congestion charge rents calculated as the difference in nodal prices between the withdrawal and injection points. These are the transmission congestion contracts (TCCs) of Harvey *et al.* [11] and, more generally, the obligation network (multiple point-to-multiple-point) rights in the proposed capacity reservation tariff [8].

One can also define *point-to-point option* rights [17] (or option TCCs [11,15]). Such rights are defined as the option but not the obligation to collect congestion rents; obviously, the option is exercised only if rents are positive. Simultaneous feasibility of rights becomes more difficult to check, since the flows implied by those rights cannot be known ahead of time unless assumptions are made about which rights will be exercised. We solve this problem by making the following conservative assumption: only balanced point-to-point option rights are traded, and they will not be exchanged in JETRA unless simultaneous feasibility can be maintained under *any* possible combination of exercised and unexercised options. As we show below [18], in the linearized DC case, this is equivalent to setting aside capacity in each transmission constraint for positive increments of flow associated with the option (positive β's resulting from positive PTDFs) but ignoring negative flows ("counterflows") (negative β's stemming from negative PTDFs). (See also [15,26].) As a result, a point-to-point option generally requires more transmission resources in (2) than does an obligation; thus, it will be more expensive to supply and will command a higher price [5,15].

The result can be phrased more formally as follows. Let $\boldsymbol{\beta_3}^{\boldsymbol{o}}$ be the matrix of β's that would be used if the $\boldsymbol{t_3}$ options were actually point-to-point obligations instead (*i.e.*, based on both positive and negative PTDFs and locations of injections, just like $\boldsymbol{t_2}$ rights). Let $\boldsymbol{\delta_n} = \{\delta_{nk}, k=1,2,\ldots,K\}$ whose elements represent whether option k is exercised ($\delta_{nk} = 1$ implies k is exercised, $\delta_{nk} = 0$ implies it is not). There are $n = 1,2,\ldots,2^K$ of these vectors, representing all possible combinations of exercised options. For instance, {1,1,1,1} means all four options are exercised, while {0,1,0,1} implies exercise of only the second and fourth options. The requirement that all the set of rights be collectively feasible for all possible combinations of exercised options implies that the following expansion of the transmission constraint set (2) be satisfied:

$$\Sigma_i \beta_{1ih} t_{1i} + \Sigma_j \beta_{2jh} t_{2j} + \Sigma_k \delta_{nk} \beta_{3kh}{}^o t_{3k} + \Sigma_m \beta_{gm} g_m \leq F_h \quad \forall h;\ n=1,..,2^K. \qquad (7)$$

Theorem 1. A vector of point-to-point options $\boldsymbol{t_3}$ satisfies (7) if and only if it satisfies the following set of constraints:

$$\Sigma_i \beta_{1i} t_{1i} + \Sigma_j \beta_{2jh} t_{2j} + \Sigma_k \mathrm{Max}(0,\beta_{3kh}{}^o) t_{3k} + \Sigma_m \beta_{gm} g_m \leq F_h \quad \forall h. \qquad (8)$$

Note that the number of constraints in set (8) is much smaller than in (7), so (8) would be more efficient to use in JETRA. This is accomplished by defining $\beta_{3kh} \equiv \mathrm{Max}(0,\beta_{3kh}{}^o)$ in (2).

Proof (see also [15,18]). It suffices to show that that any $\boldsymbol{t_3}$ that violates (8) also violates (7), while any $\boldsymbol{t_3}$ that satisfies (8) also satisfies (7). The first condition is trivial, because (8) is a subset of the constraints (7). The second condition can be shown by contradiction. Assume that some specific solution $\boldsymbol{t_3}^*$ does not violate (8) but violates at least one constraint in (7). By the definition of (8), each of those constraints in (7) that are violated must have at least one k for which $\delta_{nk} \beta_{3kh}{}^o < 0$. Because $\boldsymbol{t_3}^* \geq 0$, changing all of those negative $\delta_{nk} \beta_{3kh}{}^o$ to 0 cannot decrease the left hand side of the constraint, which means that the $\leq$ condition would remain violated. But this contradicts the assumption that (8) is satisfied, so the assumption that a constraint in (7) can be violated when there is no violation of (8) must be incorrect. **Q.E.D.**

It is possible that we have been more conservative than necessary by requiring that feasibility be maintained for all possible combinations of exercise of point-to-point options. In particular, given all the nodal prices that could result from possible generator locations, demand levels, and transmission configurations, certain combinations of options may never be exercised. As a simple example, an option from bus A to bus B will not be exercised at the same time as an exercise of an option from B to A, because only one can have a positive payment. This implies that some of the constraints in (7) (and perhaps (8)) can be dropped. However, a general procedure has not been devised for identifying combinations that will never be exercised under any set of possible nodal prices. Therefore, we recommend that our conservative procedure for including point-to-point options be adopted.

IV. FINANCIAL SETTLEMENT AND REVENUE ADEQUACY

A. *Financial Settlement*

There are various ways that forward electricity markets can be related to the real-time dispatch markets in which forward contracts are settled. There are also various roles that an RTO can play in this process. JETRA conceives of multiple forward markets to allow for reconfiguration of point-to-point obligations and options (including cashing out), along with adjustments of portfolios of flow-based rights and forward energy contracts. We emphasize again, however, that JETRA also allows operation of secondary forward markets for transmission rights and separate scheduling coordinators.

In the final JETRA iteration, which corresponds to the RTO dispatch market, only energy bids $\boldsymbol{g}$ and scheduled bilateral transactions are allowed. Bilateral transactions can be most easily modeled as $\boldsymbol{t_2}$ bids whose lower and upper bounds both equal the MW to be scheduled. Transmission constraints (2) reflect the actual state of the system. (It is possible, however, to imagine that additional transmission capacity, *e.g.*, the difference between emergency and normal MW ratings, might be also be bid in at some price in the final auction. This would be represented as a $\boldsymbol{t_1}$ bid with a negative β). This final iteration of JETRA can correspond either to the restricted energy balancing market proposed for some RTOs or the unrestricted spot markets now operating in which a day-ahead energy market is followed by a real-time market. In either case, the transmission rights are exercised in the energy dispatch market (the last JETRA iteration) using JETRA's dual variables and the LMPs derived from them.

More formally, we define a sequence of auctions JETRA^s, $s = S, S\text{-}1,\ldots,1,0$, associated with dispatch for a given hour (or other time period). Thus, JETRA^0 is the final dispatch auction. The accepted bids in JETRA^s are designated $\{\boldsymbol{t_1}^s, \boldsymbol{t_2}^s, \boldsymbol{t_3}^s, \boldsymbol{g}^s\}$, and the dual variables for the transmission constraints (2) are the vector $\boldsymbol{\mu}^s$. Let $\boldsymbol{\beta_{1i}}$ be defined as the i^{th} column of $\boldsymbol{\beta_1}$; $\boldsymbol{\beta_{2j}}$ the j^{th} column of $\boldsymbol{\beta_2}$; $\boldsymbol{\beta_{3k}}$ the k^{th} column of $\boldsymbol{\beta_3}$; and $\boldsymbol{\beta_{gm}}$ the m^{th} column of $\boldsymbol{\beta_g}$. The amounts paid by the winning bidders to the RTO are, respectively:

$$\boldsymbol{\mu}^s \boldsymbol{\beta_{1i}} t_{1i}{}^s, \forall i \qquad (9)$$

$$(\boldsymbol{\mu}^s \boldsymbol{\beta_{2j}} + \lambda^s \alpha_{2j})\, t_{2j}{}^s, \forall k \qquad (10)$$

$$\boldsymbol{\mu}^s \boldsymbol{\beta_{3k}} t_{3k}{}^s, \forall k \qquad (11)$$

$$(\boldsymbol{\mu}^s \boldsymbol{\beta_{gm}} + \lambda^s)\, g_m{}^s, \forall m \qquad (12)$$

Note that any of these amounts can be negative, representing payments from the RTO to, *e.g.*, generators. The RTO then pays following amounts to the holders of financial rights from the previous iteration JETRA^{s+1}:

$$\boldsymbol{\mu}^s \boldsymbol{\beta}_{\boldsymbol{1i}} t_{1i}^{s+1}, \forall i \tag{13}$$

$$(\boldsymbol{\mu}^s \boldsymbol{\beta}_{\boldsymbol{2j}} + \lambda^s \alpha_{2j})\, t_{2j}^{s+1}, \forall k \tag{14}$$

$$\mathrm{Max}(0, \boldsymbol{\mu}^s \boldsymbol{\beta}_{\boldsymbol{3k}}^{\boldsymbol{o}})\, t_{3k}^{s+1}\ \forall k \tag{15}$$

$$(\boldsymbol{\mu}^s \boldsymbol{\beta}_{\boldsymbol{gm}} + \lambda^s)\, g_m^{s+1}, \forall m \tag{16}$$

As we discuss further below, as long as $\{\boldsymbol{t}_1^{s+1}, \boldsymbol{t}_2^{s+1}, \boldsymbol{t}_3^{s+1}, \boldsymbol{g}^{s+1}\}$ are feasible in JETRA^s, then the RTO's revenues are sufficient to cover its payments to rights holders.

Note that (11) differs from (15); this is because t_{3k}^{s+1} is an option that is exercised only if the payment would be positive. Surprisingly, the payment (15), together with the feasibility test of Section III.C, implies that point-to-point options will be unattractive. In particular, a rational buyer would never prefer a point-to-point option $\boldsymbol{t_3}$ over a flowgate option $\boldsymbol{t_1}$ whose β_{1ih} were defined as $(0,\beta_{3kh}^o)$. This is because the buyer would pay the same amount ((9) = (11)) for either option, but could receive a greater payoff from the flowgate option ((13) > (15) if any $\mu_h\beta_{3kh}^o < 0$). Only if a less conservative feasibility test than (8) is used for point-to-point options (decreasing its selling price relative to flowgate options) could such options be advantageous. Thus, further research is desirable on such tests that would still ensure revenue adequacy.

There could be several alternative rules for initial allocations of rights and for carrying rights purchased in one stage to the next stage. Initial allocations could be based on the auction, or could be given away to facility owners and/or load serving entities. There are also different ways that rights holders can hold their positions. Bidding a maximum amount $\boldsymbol{T_{U1}}$, $\boldsymbol{T_{U2}}$, $\boldsymbol{T_{U3}}$, or $\boldsymbol{G_U}$ equal to the current rights held with very large values of $\boldsymbol{b_1}$, $\boldsymbol{b_2}$, $\boldsymbol{b_3}$, or $\boldsymbol{b_g}$ should suffice. So would setting the upper and lower bounds equal to the desired amount of rights. The RTO could either require rights holders to submit such bids or lose the rights, or it could presume that holders wish to stay put unless they otherwise say so. As noted above, however, no financial rights are bid or traded in the final iteration JETRA^0, and all users of the transmission grid must submit physical bids $\boldsymbol{g}$ or bilateral schedules.

B. Revenue Adequacy

The auctions retain revenue adequacy (that is, financial integrity) if the RTO collects enough revenue from transmission services buyers to cover the payments it has to make to holders of financial transmission rights. Conceptually, if all transmission users pay marginal congestion costs, then the RTO should be revenue adequate if the aggregate of transmission rights does not result in violation of transmission constraints in JETRA (assuming convexity of the transmission constraints). However, if the RTO oversells transmission rights or if users of the system are not charged marginal costs, then revenue may be insufficient.

Theorem 2. Let $\boldsymbol{F}^{s+1} \leq \boldsymbol{F}^s$ and $\boldsymbol{\beta}_{\boldsymbol{l}}^{\,s} \leq \boldsymbol{\beta}_{\boldsymbol{l}}^{\,s+1}$ for l = 1,2,3. (Note that $\boldsymbol{X} \leq \boldsymbol{Y}$ means that $x_i \leq y_i, \forall i$.) Then JETRA is revenue adequate, *i.e.*, RTO payments to rights holders (9)-(12) do not exceed RTO receipts from rights buyers (13)-(16):

$$\begin{aligned}\boldsymbol{\mu}^s\boldsymbol{\beta}_1\boldsymbol{t}_1^{s+1} + (\boldsymbol{\mu}^s\boldsymbol{\beta}_2+\lambda^s\boldsymbol{\alpha}_2)\boldsymbol{t}_2^{s+1} + \Sigma_k\,\mathrm{Max}(0,\boldsymbol{\mu}^s\boldsymbol{\beta}_{\boldsymbol{3k}}^{\boldsymbol{o}})t_{3k}^{s+1} \\ + (\boldsymbol{\mu}^s\boldsymbol{\beta}_g+\lambda^s)\boldsymbol{g}^{s+1} \\ \leq\ \boldsymbol{\mu}^s\boldsymbol{\beta}_1\boldsymbol{t}_1^{s} + (\boldsymbol{\mu}^s\boldsymbol{\beta}_2+\lambda^s\boldsymbol{\alpha}_2)\boldsymbol{t}_2^{s} + \boldsymbol{\mu}^s\boldsymbol{\beta}_3\boldsymbol{t}_3^{s} + (\boldsymbol{\mu}^s\boldsymbol{\beta}_g+\lambda^s)\boldsymbol{g}^{s}.\end{aligned} \tag{17}$$

Proof. This first part of the proof proceeds in a way broadly analogous to the revenue adequacy proof in [13], and the second half extends the result to point-to-point options. First, the complementary slackness condition for the transmission capacity constraints implies that:

$$\boldsymbol{\mu}^s(\boldsymbol{\beta}_1^{\,s}\,\boldsymbol{t}_1^{\,s} + \boldsymbol{\beta}_2^{\,s}\,\boldsymbol{t}_2^{\,s} + \boldsymbol{\beta}_3^{\,s}\,\boldsymbol{t}_3^{\,s} + \boldsymbol{\beta}_g^{\,s}\,\boldsymbol{g}^{\,s}) = \boldsymbol{\mu}^s\boldsymbol{F}^s. \tag{18}$$

We know that the existing rights are feasible in iteration s+1, $\boldsymbol{\beta}_1^{\,s+1}\,\boldsymbol{t}_1^{\,s+1} + \boldsymbol{\beta}_2^{\,s+1}\,\boldsymbol{t}_2^{\,s+1} + \boldsymbol{\beta}_3^{\,s+1}\,\boldsymbol{t}_3^{\,s+1} + \boldsymbol{\beta}_g^{\,s+1}\,\boldsymbol{g}^{\,s+1} \leq \boldsymbol{F}^{\,s+1}$. Hence, since $\boldsymbol{\beta}_{\boldsymbol{l}}^{\,s} \leq \boldsymbol{\beta}_{\boldsymbol{l}}^{\,s+1}$ for l = 1,2,3, and $\boldsymbol{F}^s \geq \boldsymbol{F}^{s+1}$, we have:

$$\boldsymbol{\beta}_1^{\,s}\,\boldsymbol{t}_1^{\,s+1} + \boldsymbol{\beta}_2^{\,s}\,\boldsymbol{t}_2^{\,s+1} + \boldsymbol{\beta}_3^{\,s}\,\boldsymbol{t}_3^{\,s+1} + \boldsymbol{\beta}_g^{\,s}\,\boldsymbol{g}^{\,s+1} \leq \boldsymbol{F}^s. \tag{19}$$

Remembering that $\boldsymbol{\mu}^s \geq 0$, and then invoking (18), we obtain:

$$\begin{aligned}\boldsymbol{\mu}^s(\boldsymbol{\beta}_1^{\,s}\,\boldsymbol{t}_1^{\,s+1} + \boldsymbol{\beta}_2^{\,s}\,\boldsymbol{t}_2^{\,s+1} + \boldsymbol{\beta}_3^{\,s}\,\boldsymbol{t}_3^{\,s+1} + \boldsymbol{\beta}_g^{\,s}\,\boldsymbol{g}^{\,s+1}) \leq \boldsymbol{\mu}^s\boldsymbol{F}^s \\ = \boldsymbol{\mu}^s(\boldsymbol{\beta}_1^{\,s}\,\boldsymbol{t}_1^{\,s} + \boldsymbol{\beta}_2^{\,s}\,\boldsymbol{t}_2^{\,s} + \boldsymbol{\beta}_3^{\,s}\,\boldsymbol{t}_3^{\,s} + \boldsymbol{\beta}_g^{\,s}\,\boldsymbol{g}^{\,s}).\end{aligned} \tag{20}$$

By definition of the energy balance (3), $\boldsymbol{\alpha}_2\,\boldsymbol{t}_2^s + \boldsymbol{\imath}\,\boldsymbol{g}^s = 0 = \boldsymbol{\alpha}_2\,\boldsymbol{t}_2^{s+1} + \boldsymbol{\imath}\,\boldsymbol{g}^{s+1}$. Therefore the following is true for any λ:

$$\lambda^s(\boldsymbol{\alpha}_2\,\boldsymbol{t}_2^{s+1} + \boldsymbol{\imath}\,\boldsymbol{g}^{s+1}) = \lambda^s(\boldsymbol{\alpha}_2\,\boldsymbol{t}_2^{s} + \boldsymbol{\imath}\,\boldsymbol{g}^{s}). \tag{21}$$

We now add (20) and (21); after rearrangement:

$$\begin{aligned}\boldsymbol{\mu}^s\boldsymbol{\beta}_1\boldsymbol{t}_1^{s+1} + (\boldsymbol{\mu}^s\boldsymbol{\beta}_2+\lambda^s\boldsymbol{\alpha}_2)\boldsymbol{t}_2^{s+1} + \boldsymbol{\mu}^s\boldsymbol{\beta}_3\boldsymbol{t}_3^{s+1} + (\boldsymbol{\mu}^s\boldsymbol{\beta}_g+\lambda^s)\boldsymbol{g}^{s+1} \\ \leq\ \boldsymbol{\mu}^s\boldsymbol{\beta}_1\boldsymbol{t}_1^{s} + (\boldsymbol{\mu}^s\boldsymbol{\beta}_2+\lambda^s\boldsymbol{\alpha}_2)\boldsymbol{t}_2^{s} + \boldsymbol{\mu}^s\boldsymbol{\beta}_3\boldsymbol{t}_3^{s} + (\boldsymbol{\mu}^s\boldsymbol{\beta}_g+\lambda^s)\boldsymbol{g}^{s}.\end{aligned} \tag{22}$$

Now note that:

$$\begin{aligned}\boldsymbol{\mu}^s\boldsymbol{\beta}_3\,\boldsymbol{t}_3^{s+1} &\equiv \Sigma_k\,[\Sigma_h\,\mu_h^s\,\mathrm{Max}(0,\beta_{3kh}^o)t_{3k}^{\,s+1}] \\ &= \Sigma_k\,[\mathrm{Max}(0,\Sigma_h\,\mu_h^s\,\mathrm{Max}(0,\beta_{3kh}^o)t_{3k}^{\,s+1})] \\ &\geq \Sigma_k\,[\mathrm{Max}(0,\Sigma_h\,\mu_h^s\,\beta_{3kh}^o\,t_{3k}^{\,s+1})] \\ &= \Sigma_k\,\mathrm{Max}(0,\boldsymbol{\mu}^s\boldsymbol{\beta}_{\boldsymbol{3k}}^{\boldsymbol{o}})t_{3k}^{s+1}.\end{aligned} \tag{23}$$

The first line is the definition of β_{3kh} from Section III.C. The equality in the second line results from the facts that μ_h^s, t_{3k}^{s+1}, and $\mathrm{Max}(0,\beta_{3kh}^o)$ are all nonnegative. The inequality results from $\mathrm{Max}(0,\beta_{3kh}^o) \geq \beta_{3kh}^o$. The final line follows from the definition of $\boldsymbol{\beta}_{\boldsymbol{3k}}^{\boldsymbol{o}}$ and from $t_{3k}^{s+1} \geq 0$. We now substitute the last line in (23) for $\boldsymbol{\mu}^s\boldsymbol{\beta}_3\boldsymbol{t}_3^{s+1}$ in (22). **Q.E.D.**

This proof can be easily generalized to account for sales of options by bidders; but for conciseness, we omit that detail.

In essence, if the feasible region defined by the transmission constraints does not shrink from iteration to iteration, the payments to rights holders will never exceed the revenue obtained from JETRA. Of course, there is always the possibility of an outage contingency not considered in the transmission constraints (2); its occurrence would violate the assumption of the proof that $\boldsymbol{F}$ does not shrink, and congestion revenue might fall short of payments to right holders in the real-time auction. The RTO could deal with the deficit in several ways: socialize costs by raising grid access fees or taxing JETRA participants; dip into a balancing fund built up from periods when revenues exceeded rights payments; extract compensation from the owner of the failed facility; or prorate rights payments, as in PJM.

V. NUMERICAL EXAMPLE

Table I shows the assumed coefficients and results for an iteration of JETRA for a triangular transmission network consisting of three identical transmission lines (each with capacity 100 MW in each direction) connecting three busses (designated D, E, and F) (Fig. 1). Thus, there are six flowgate constraints, one in each direction on each line. The PTDFs for a power transfer from one bus to another are 2/3 for the line constraint directly connecting the two busses and 1/3 for the other two lines (with, of course, negative PTDFs for constraints in the direction opposite to the induced flow). In round *s* of this JETRA we assume the following bidders:

- Three flowgate ($\boldsymbol{t_1}$) bidders for three separate flowgates.
- Two point-to-point bidders. One is a balanced obligation from D to F having both negative and positive PTDFs in the transmission constraints ($t_{2,1}$), and the other is a balanced option from D to E whose β's reflect only its positive PTDFs ($t_{3,1}$).
- Two forward energy bidders ($\boldsymbol{g}$) at two distinct locations, the first a seller and the second a buyer.

The first row of values in Table I shows the amount ($/MW) each bidder is willing to pay (or receive, in the case of the energy seller), and the next two rows show the lower and upper bounds on the quantities they want to buy. The third bidder $t_{1,3}$ gives a lower bound of 50 MW to the amount of rights it desires, and so is implicitly willing to pay any amount for those rights; the other bidders have lower bounds of zero.

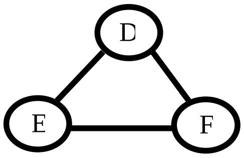

Fig. 1. Example Three Node Network (100 MW Limit on Each Line)

The amount of rights to each flowgate that each bidder requests is reflected in the β coefficients in Table 1 for each of the six constraints. For instance, the second flowgate bidder $t_{1,2}$ is interested only in the third flowgate (representing the constraint from E to F), and so has a 1 in that row and zeroes elsewhere. Meanwhile, the point-to-point obligation bidder $t_{2,1}$ would inject power at node D and remove it at node F. Based on the PTDFs for this simple system, two-thirds of the flow takes place over the line connecting D and F; hence, the β coefficient for the flowgate D→F is 2/3. Of course, in the opposite direction F→D, the coefficient is instead –2/3. One-third of the power flows over each of the other two lines, and their β's reflect this fact. As a final example, as our PTDFs rely on node D being the hub, a 1 MW energy withdrawal by bid g_2 at node F will result in 2/3 MW flowing directly from D to F, and 1/3 MW flowing indirectly from D to F via E.

To the right of the β's, the table shows the values of the left- and right-hand sides of the constraints, and their duals.

After maximizing the net value of the bids subject to simultaneous feasibility, the accepted bid quantities (MW) in the fourth row result. Each of the bidders pay the RTO the amount shown in the fifth row, based on the above payment formulas and the dual variables displayed next to the transmission capacities in Table 1. Three of six bidders get the maximum MW they request ($t_{1,2}$, $t_{3,1}$, and g_2), one bidder obtains its minimum ($t_{1,3}$), and the others receive amounts in between. Bidder $t_{1,3}$ got only its minimum even though it offered a higher price ($9/MW) than any other flowgate bidder. This is because its bid for the flowgate it wants (D→F) was less than the worth of that flowgate to the point-to-point and energy bidders, who would heavily use that flowgate.

The payments that the bidders make to the RTO vary greatly. Flowgate bidder $t_{1,2}$ pays nothing for its rights, because there are more rights available than the bidders can use. On the other extreme, flowgate bidder $t_{1,3}$ pays dearly for its rights because they are very valuable to other bidders. The RTO pays $750 to energy supplier g_1 in exchange for its forward commitment to provide 30 MW. Because of transmission congestion, that amount is less than the $1050 that energy consumer g_2 pays the RTO for its rights to 30 MW. The sum of payments from all bidders to the RTO equals $1650.

The revenue adequacy theorem guarantees that this amount will be no less than payments to previous rights holders if those rights are simultaneously feasible under the constraints. The next-to-last row of the table shows an assumed set of rights awarded in previous auction *s*+1 that entitle holders to compensation from this auction *s*. Multiplying those existing rights by the β's shows that none of the flowgate limits of 100 MW would be violated. Thus, we ought not be surprised that the total payment of $1620 by the RTO to these rights holders, as calculated by (13)-(16), is less than payments (9)-(12) to the RTO by the new rights holders. (Note that the amount that the point-to-point option right holder can receive must be calculated based on the full set of PTDFs for that right, not just the positive values shown in its β column, and furthermore is paid only if the total is nonnegative. The calculated $130 is indeed positive, and so the option is exercised and that amount paid.)

This example also shows how a rights holder can reconfigure its rights. For instance, the bidder represented by $t_{1,2}$ previously owned 60 MW of rights to that flowgate. Its 50 MW lower bound in round *s* represents a desire to retain at least 50 MW of those rights for the future (and a willingness to sell 10 MW of rights). Meanwhile its upper bound of 100 MW shows that, given the right price, it would be willing to buy up to 40 MW more of those rights than it now owns.

VI. CONCLUSION

Efficient congestion management and tradable transmission rights that fit the needs of diverse users of the grid are essential to the development of RTO markets. Two sophisticated, and evolving, paradigms for transmission rights are currently recognized as the way forward: point-to-point contracts and the flow-based right. Both types of rights are compatible with locational marginal pricing of energy. Both have advantages and disadvantages from the perspective of different market participants. The joint energy and transmission rights auction proposed here allows transmission users to specify which type of rights they prefer and reconfigure them over time, while establishing rules that limit the need to subsidize these markets as they develop. Furthermore, JETRA is innovative in allowing trade in point-to-point options.

TABLE I.
JETRA EXAMPLE: ASSUMPTIONS, RIGHTS ALLOCATION, RTO RECEIPTS, AND RTO PAYMENTS TO RIGHTS HOLDERS

Variable name:	$\underline{t_{1,1}}^{s}$	$\underline{t_{1,2}}^{s}$	$\underline{t_{1,3}}^{s}$	$\underline{t_{2,1}}^{s}$	$\underline{t_{3,1}}^{s}$	$\underline{g_{1}}^{s}$	$\underline{g_{2}}^{s}$			
Bid *b* ($/MW):	3	6	9	10	7	-25	40			
Lower Bound (MW):	0	0	50	0	0	0	0			
Upper Bound (MW):	80	70	100	80	50	40	30			
Optimal Value (MW):	50	70	50	20	50	30	30			
RTO Receipt ($):	150	0	675	200	325	-750	1050	Left-hand side (MW)	Right-hand side (MW)	Dual ($/MW)
Constraints		Constraint	Coefficients	(MW/MW)						
D → E:	1	0	0	1/3	2/3	0	1/3	100	100	3
E → D:	0	0	0	-1/3	0	0	-1/3	-16.67	100	0
E → F:	0	1	0	1/3	0	0	1/3	86.67	100	0
F → E:	0	0	0	-1/3	1/3	0	-1/3	0	100	0
D → F:	0	0	1	2/3	1/3	0	2/3	100	100	13.5
F → D:	0	0	0	-2/3	0	0	-2/3	-33.33	100	0
Energy balance:	0	0	0	0	0	-1	1	0	0	25
Previous Rights Holders:	$\underline{t_{1,1}}^{s+1}$	$\underline{t_{1,2}}^{s+1}$	$\underline{t_{1,3}}^{s+1}$	$\underline{t_{2,1}}^{s+1}$	$\underline{t_{3,1}}^{s+1}$	$\underline{g_{1}}^{s+1}$	$\underline{g_{2}}^{s+1}$			
Value (MW):	60	60	60	50	20	0	0			
Payment from RTO ($):	180	0	810	500	130	0	0			

Elsewhere [18], versions of JETRA are proposed that include more general nonlinear transmission relationships while remaining revenue adequate. Potentially useful linearizations of the nonlinear models are presented, including piecewise linearizations of transmission losses (similar to [20]) and linear dual models for calculating shadow prices. Ongoing work at FERC is addressing market power in transmission markets and incentives for transmission investment.

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VIII. BIOGRAPHIES

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