The Economic Evaluation of System Security Criterion in a Competitive Market Environment

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1 Introduction

In the restructured environment, the improvement of the economic efficiency of electricity markets has been the focus of recent efforts [1, 2]. Central to these efforts is the better understanding of the nature of the tight coupling between market and system operations. An important aspect of this coupling is the dependence of the market outcomes on the way the system is operated. A key driver in system operations is the security criterion, with which compliance must be ensured. The focus of this work is the dependence of market performance on system security. In this work, we propose an approach to quantify the market performance as a function of a specified security criterion for both single- and multi-settlement environments. We illustrate the application of the proposed approach on the large-scale ISO-NE system.

System security is defined as the ability of the interconnected system to provide electricity with the appropriate quality under normal and contingency conditions [3]. The security criterion consists of the set of postulated contingencies and the associated preventive and/or corrective control actions [4]. For a given operating

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state, security assessment entails the verification that no violation occurs for any of the postulated contingencies taking fully into account the deployment of the associated security control actions. As these actions affect the market outcomes, a key step in the efforts to improve market performance is the assessment of these impacts of complying with the security criterion in monetary terms. Such studies are, typically, not performed by today's large regional transmission organizations, or RTOs. Consequently, there is a need for an appropriate methodology to quantitatively measure the market performance impacts of complying with security criterion.

Under single-settlement systems, a market trades the electricity commodity that is physically produced and consumed. However, the design and implementation of electricity markets in many jurisdictions involves two or more inter-related markets that are cleared at different points in time. The sequence of markets trades the commodity that is physically produced and consumed in real time. Each market, be it a day-ahead hourly market (DAM) or one of the real-time markets (RTMs) associated with that hour, trades the MWh commodity at different prices that reflect the information on the system and market conditions available at the time the MWh commodity is cleared. As these conditions are subject to continuous changes in real time, real-time markets (RTMs) are cleared at a high frequency, typically every 5 min. On the other hand, markets run ahead of real-time system operations have a lower clearing frequency, e.g. hourly clearing in the day-ahead markets, reflecting the lower resolution of the imperfect information on the real-time conditions in the next day. The hour *h* DAM is cleared on the forecasts of the real-time conditions for that hour the next day. The hourly clearing influences each RTM in the near-real-time during that hour. The RTM clearing determines the volume of deviations from the hour h DAM value and the associated price. Such a market design with different lead times and clearing frequencies is commonly referred to as a multi-settlement system [5–7].

The RTO or the independent system operator (ISO) manages system operations through market forces. The various inter-relationships between the physical network security management and the clearing of a single market or the sequence of markets imply the strong interdependence between system security and market outcomes. Although the DAMs are financial markets in contrast to the purely physical RTMs, both markets are cleared using the same approach. A key difference between these markets is the nature of the participants. While financial entities may participate in the DAMs, only players with physical resources or loads can participate in the RTMs. In addition, while the demand may be price responsive in the DAMs, the demand is, typically, fixed in the RTMs. As the DAM outcomes impact the associated RTMs, financial entities may very well impact the system operations in real-time.

The economic efficiency of electricity markets under single-settlement systems is analyzed in various contexts by both empirical and analytical means. The empirical studies investigate the adverse impacts of market participants' behaviors on the performance of electricity markets [8–11]. The analytical studies, on the other hand, focus on the impacts of constrained system operations on markets to determine the unavoidable losses in the economic efficiency of electricity markets [12, 13]. The interactions between the system security criterion and the associated economics are investigated in terms of the marginal costing—used to determine the security prices—and the evaluation of expected system security costs. The security prices, determined in this way, explicitly incorporate the willingness of the market participants to provide security control capability into the market clearing process [14–16]. The expected system security costs are evaluated taking explicitly into account the random nature of the outages and the costs of the required security control actions to deal with them [17, 18]. A key result of [18] is that the security criterion may be set by the cost/benefit analysis taking into account the expected costs of operating the system and the expected outage costs. Such an approach may be viewed as the application of the notion of "value of reliability" introduced in [19] which was used for operational planning purposes [20]. However, there is a clear need, in the restructured environment, to quantify the market performance as a function of system security in a way that appropriately reflects the RTO operations. This quantification further requires the consideration of different market and system conditions that may exist within a period in order to capture the range of impacts under such conditions.

The economic benefits of multi-settlement systems have been previously analyzed [7, 21–23]. The study in [7] discusses the role of the DAMs in terms of providing incentives for accurate forecasts in real-time operations and for facilitating trades through ex-ante price discovery. The duopoly model in the simple two-node network shows that for small probabilities of congestion, multi-settlement systems are welfare-enhancing when compared to single-settlement market designs [21]. The analysis of the impacts of congestion in a multi-settlement environment makes clear that the welfare-enhancing role of multi-settlement system is highly sensitive to the presence of real-time congestion [22]. Further evidence of the welfare-enhancing impacts of multi-settlement systems comes from the empirical analysis of the PJM and NY-ISO markets [23]. We note that when the market design misaligns system and market operations, as was the case in the California prior to the 2000–2001 crisis, the market participants may manipulate markets resulting in decreased overall market performance [24]. Much of the analysis of the role of financial entities has a focus on the monetary impacts of such participants [25–27]. As the participation of financial entities not only increases market liquidity but may also result in price convergence, multi-settlement systems are viewed as improving the economic efficiency of electricity markets when compared to the single-settlement markets [25–27]. The ISO-NE study [25] identifies that after the introduction of "virtual bidding", the actual offer/bid mechanism that enables financial entity participation in the DAMs, the RTM and DAM prices tend to converge. The convergence implies an improvement in market performance as temporal arbitrage opportunities diminish. Under speculative trading, financial entity participation may lead to increased market efficiency and decreased average electricity price [26]. The inter-relationship between the price convergence and the profits of the financial entities is a "self-correcting" feature of multi-settlement systems [27]. As such, multi-settlement systems provide appropriate price signals to the financial entities, which they may use to make profitable trades that may lead to price convergence. On the other hand, the discussion of the impacts of the behavior of the financial entities driven by such price signals on the real-time system security is absent in the literature.

The provided literature review pinpoints the specific needs in better understanding and quantifying of the tight coupling between system and market operations. An important need is an integrated analysis approach to quantify the interdependence between the market performance and the way the power systems are operated to ensure security that appropriately reflects the actual RTO operations. Furthermore, such a need has to take into account the multi-settlement environment. Specifically, there is a clear need to analyze whether the behavior of financial entities driven by price signals can impact, in some measurable way, system security. We address these and other related issues in the analysis and economics of power system security in the competitive environment by proposing a set of appropriate approaches and tools that are effective for the analysis and quantification of a wide range of issues for large-scale networks that we encounter in actual power systems. We illustrate a number of representative applications on the large-scale ISO-NE system and discuss the insights we obtain from our studies.

The highly challenging task of security management becomes even more complex in the competitive market environment. We use the insights we developed into the tight coupling between market and system operations under restructuring to characterize analytically the inter-relationships between the way the power systems are operated and the performance of the electricity markets. Such characterization leads us to the development of a systematic approach that quantifies the market performance as a function of security criterion under diverse system and market conditions for single-settlement systems. This approach permits the quantification of the market performance impacts arising from a change from a given to another security criterion. The approach provides, for the first time, an economic justification for the RTO decision to modify the security criterion. Furthermore, the approach can be used in the cost/benefit analysis of network improvements to mitigate the market performance impacts of a set of contingencies or their associated security control actions. Another application of the approach is to the assessment of the impacts of specific behavioral changes in market participants on system security.

We extend this approach to quantitatively characterize the linkages between the real-time system operations and the DAMs and their associated RTMs for a multi-settlement environment. We explicitly show with the extended approach that the auction surplus attained in the multi-settlement system is equivalent to the sum of the auction surpluses attained in each RTM. Therefore, the mere presence of the DAMs results in surplus transfers among market participants. Furthermore, the extended approach provides a very useful tool to analyze the nature of the DAM-RTM price deviations and the impacts of financial entities on real-time system security.

We illustrate the application of the approaches on the large-scale ISO-NE system using the historical 2005–2006 data—the system model and the bids/offers submitted—and the actual market clearing methodology. The large-scale ISO-NE DAM application study provides important insights into the role of price-responsive demand and selected security control actions by demonstrating that the economic efficiency of the electricity markets need not decrease when a power system is operated under a stricter criterion, as long as there is effective price-responsive demand and appropriate utilization of the corrective control capabilities of the resources. The ISO-NE multi-settlement application study bear out the well known fact that the participation of financial entities leads to the convergence of the DAM and the associated RTM prices. Moreover, the study also illustrate that such participation leads to improved forecasts of the real-time system operations, and consequently results in improving the assurance of system security.

This chapter contains six additional sections. The market performance quantification for a system snapshot is described in Sect. 2. We devote Sect. 3 to extension of the quantification to the multi-settlement environment. In Sect. 4, we describe the proposed approach and discuss its possible applications. In Sect. 5, we apply the proposed approach to the ISO-NE system and present the study results in detail. We conclude in Sect. 6 with a summary of the work.

2 Market Assessment for a System Snapshot

We introduce specific assumptions on unit commitment decisions, ancillary services and the market participants' behaviors so as to allow the side-by-side comparison of different security criteria impacts for a given system. We assume that the unit commitment decisions fully reflect the requirements of the security criterion under consideration. In particular, this assumption ensures the feasibility of meeting the system fixed demands under such a criterion. As the focus of this investigation is limited to energy only markets, we assume that the ancillary services provision and acquisition requirements under the RTO framework do not impose any additional constraints on the system. For the purposes of this study, we furthermore assume that the bidding behavior of each market participant is independent of the security criterion in force. Since we replicate the RTO actions, we ensure compliance with the security criterion in force, but implicitly ignore the probability of any contingency in the studies.

We associate a security criterion C with a specific contingency list and a specified control action (preventive or corrective) for every contingency on that list. A preventive control action associated with a postulated contingency entails the modification of the pre-contingency—base case—state, to eliminate any potential violation, if that contingency were to occur. On the other hand, an associated corrective control action may involve the modification of both the pre- and the post-contingency states. The modification of the pre-contingency state involves steering the operating point into a state in which the RTO is able to modify the resources' dispatch, including those of both load and generation, to alter the post-contingency state only after the contingency actually occurs.

As such, there may be no change in resource utilization if the contingency fails to happen. For some contingencies, such as a generator outage or a sudden load change, the RTO may take only corrective control actions.

We consider a power system consisting of $(N+1)$ nodes and denote by $\mathbf{N} = \{0, 1, \ldots, N\}$ the set of buses, with the slack bus at bus *0.* The security criterion C has the contingency list $\mathbf{J}_C$ and the specified control action for each contingency. Let $\mathbf{S}$ ($\mathcal{B}$) denote the collection of sellers (buyers). Each seller (buyer) submits its price and quantity offer (bid), indicating the willingness to sell (buy) the amount of energy for the duration represented by the snapshot to (from) the RTO. We note that the offers and bids need not necessarily be the true marginal costs and benefits of the participants [28–30]. We represent a bilateral transaction ω_w by $\omega_w = \{m_w, n_w, \bar{t}_w\}$. Here, m_w denotes the *from* node, n_w the *to* node, and $\bar{t}_w$ the desired transaction amount. The set of all the bilateral transactions is denoted by $\boldsymbol{W} = \{\omega_1, \ldots, \omega_W\}$. Each transaction submits a willingness to pay function, which states a willingness to pay maximum transmission usage fees for receiving the requested transmission services as a function of the transaction amount delivered [31]. The RTO weighs the willingness to pay of the bilateral transactions with that of the individual market participants to determine the amount of transmission service provision to each player. For this purpose for a given snapshot of the system, the RTO solves a security-constrained OPF, or SCOPF, problem with the objective to maximize the auction surplus under the security criterion C whose contingency index set is denoted by $\mathbf{J}_C$. We state the SCOPF problem as

$$\max\ \mathbf{S} \triangleq \sum_{i=0}^{N} \left(\sum_{b \in \mathcal{B} \text{ at node } i} \beta_b(p_b) - \sum_{s \in \mathbf{S} \text{ at node } i} \beta_s(p_s) \right) + \sum_{w=1}^{W} \alpha_w(t_w) \tag{1}$$

subject to

$$\underline{g}^{(0)}\left(\underline{p}_s^{(0)}, \underline{p}_b^{(0)}, \underline{t}^{(0)}, \underline{\chi}^{(0)}, \underline{\gamma}^{(0)}\right) = \underline{0} \leftrightarrow \underline{\lambda}^{(0)} \tag{2}$$

$$\underline{h}^{(0)}\left(\underline{p}_s^{(0)}, \underline{p}_b^{(0)}, \underline{t}^{(0)}, \underline{\chi}^{(0)}, \underline{\gamma}^{(0)}\right) \leq \underline{0} \leftrightarrow \underline{\mu}_h^{(0)} \tag{3}$$

and for every $j \in \boldsymbol{J}_C$.

$$\underline{g}^{(j)}\left(\underline{p}_s^{(j)}, \underline{p}_b^{(j)}, \underline{t}^{(j)}, \underline{\chi}^{(j)}, \underline{\gamma}^{(j)}\right) = \underline{0} \leftrightarrow \underline{\lambda}^{(j)} \tag{4}$$

$$\underline{h}^{(j)}\left(\underline{p}_s^{(j)}, \underline{p}_b^{(j)}, \underline{t}^{(j)}, \underline{\chi}^{(j)}, \underline{\gamma}^{(j)}\right) \leq \underline{0} \leftrightarrow \underline{\mu}_h^{(j)} \tag{5}$$

$$\left| \underline{p}_s^{(j)} - \underline{p}_s^{(0)} \right| \leq \underline{\Delta p}_s^{(j)} \leftrightarrow \underline{\mu}_s^{(j)} \tag{6}$$

$$\left| \underline{p}_b^{(j)} - \underline{p}_b^{(0)} \right| \leq \underline{\Delta p}_b^{(j)} \leftrightarrow \underline{\mu}_b^{(j)} \tag{7}$$

$$\left|\underline{t}^{(j)} - \underline{t}^{(0)}\right| \leq \underline{\Delta t}^{(j)} \leftrightarrow \underline{\mu}_t^{(j)} \quad (8)$$

Here, we consider a lossless system and use the superscript (*j*) to denote the contingency cases with the base case denoted by (0). The vector associated with the right-hand side of a constraint is the dual variable of that constraint. The relations in Eqs. 2 and 3 represent the operational constraints for the base case, while those in Eqs. 4–8 represent the operational constraints for the contingency cases. The $|\boldsymbol{J}_C|+1$ equality constraints in Eqs. 2 and 4 state the nodal power balance equations for the base case and for each postulated contingency case, respectively. The base case (Eq. 3) and contingency case (Eq. 5) inequality constraints state the system components' operational limits, as well as, the so-called generic limitations representing the physical, engineering and policy considerations. The range of the decision variables of the security control action for each contingency $j \in \boldsymbol{J}_C$. is given in Eqs. 6–8 together with the limiting values of these ranges. The preventive control actions have a zero range in contrast to the corrective actions whose non-zero range reflects the additional flexibility to address the onset of the contingency. Note that, in the SCOPF, we explicitly take into account the costs of modifying the pre-contingency state but ignore any costs related to the post-contingency state modification. We denote the security-constrained market problem Eqs. 1–8 by $\mathcal{M}(\mathcal{S}, \mathcal{B}, \mathcal{W}; \mathcal{C})$.

We distinguish between fixed demand buyers and those with price-responsive demand. The fixed demand bid is a special case of the price-sensitive bid in which a specified quantity is submitted with no price information. Such a bid indicates an unlimited willingness to pay for the electricity purchases to meet the fixed quantity bid, i.e., the buyer is willing to pay any price to obtain the electricity. There are, however, difficulties in determining the appropriate value of the benefits of such fixed demand buyers. In order to include these buyers' benefits in the objective function of the $\mathcal{M}(\mathcal{S}, \mathcal{B}, \mathcal{W}; \mathcal{C})$, we use a constant τ per MWh benefit value for the fixed demand, where τ is set to have a high value to indicate the payments that may be incurred due to outages, say as much as 10,000 \$/MWh [32].

The market performance of the snapshot system under the specified security criterion C is quantified from the market clearing given by the solution of $\mathcal{M}(\mathcal{S}, \mathcal{B}, \mathcal{W}; \mathcal{C})$. We quantify the market performance in dollar terms on a system-wide basis, as well as for each individual market participant. We use the optimal auction surplus attained under C as the measure of the overall economic performance of the market.[1] As market participants are not obligated to reveal their actual costs and benefits, we use the bids and the offers to evaluate the bid/offer

[1] In a highly competitive market environment with a uniform price auction mechanism, the market participants tend to reveal their true marginal costs and benefits. Under such conditions, the auction surplus becomes a good proxy for the social welfare and, therefore, an appropriate approximation of the economic efficiency of the markets.

surplus of each participant at the optimum of Eqs. 1–8. We denote the values of the optimal variables by the superscript *. The seller s at node i has an offer surplus of

$$S_s = \lambda_i^* p_s^* - \beta_s(p_s^*) \tag{9}$$

where, λ_i^* is the locational marginal price (LMP) at node i, i.e. the price at which each MWh at node i is bought and sold. The bid surplus of the buyer b with demand at node i is similarly given by

$$S_b = \beta_b\left(p_b^*\right) - \lambda_i^* p_b^* \tag{10}$$

When the grid becomes constrained, the LMP at each node may change: in fact, for a lossless system, the non-zero LMP difference provides a measure of the congestion impacts. Absent congestion, the revenues collected in a lossless system from the buyers exactly equal the payments made to all the sellers. When congestion occurs, however, the two quantities are no longer equal. The difference between the revenues and the payments

$$K = \sum_{i=I}^{N} \sum_{b \in \mathcal{B} \text{ at node } i} \lambda_i^* p_b^* - \sum_{i=I}^{N} \sum_{s \in \mathcal{S} \text{ at node } i} \lambda_i^* p_s^* + \sum_{w=1}^{W} \left(\lambda_{m_w}^* - \lambda_{n_w}^*\right) t_w^* \tag{11}$$

is the congestion rents collected by the RTO, with the last term in Eq. 11 being the payments by the bilateral transactions.

We use the total dispatched load to evaluate the total cleared demand quantity under C

$$P_B = \sum_{b \in \mathcal{B}} p_b^* + \sum_{w=1,}^{W} t_w^* \tag{12}$$

In the next section, we extend the snapshot quantification approach for a multi-settlement environment.

3 Market Performance Quantification of a DAM and of its associated RTMs

In a multi-settlement environment, we deal with inter-related electricity markets. The actual system conditions during the hour h may differ from those used to determine the DAM hour h outcomes. The RTO uses market forces to manage such deviations and runs the RTMs, typically, every 5–10 min. As such, we may refer to RTMs as balancing energy markets. We associate with the DAM $\mathcal{D}_h$ for the hour h, the M RTMs $\mathcal{R}|_{(h,1)}\mathcal{R}|_{(h,2)}, \ldots, \mathcal{R}|_{(h,M)}$.

The DAMs are 24 separate hourly energy markets, one for each hour of the next day. Their financial nature makes possible the participation of financial entities, in addition to the players with physical resources. We use a snapshot to represent the

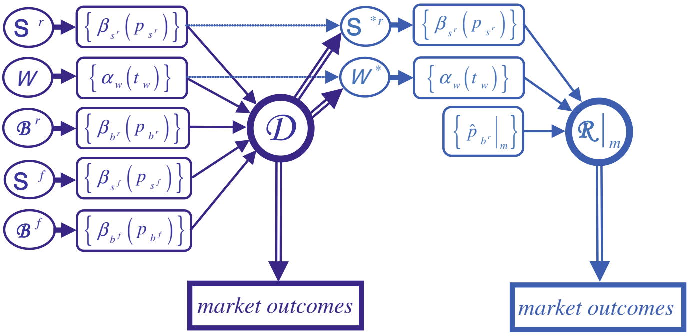


Fig. 1 Information flow in $\mathcal{D}$ for a given hour and an associated $\mathcal{R}|_m$

system for the hour h DAM and an "updated" snapshot for each $\mathcal{R}_{(h,m)}$, $m = 1, \ldots, M$. In what follows, we suppress the hour h notation so as to simplify the notation. We analyze the hour h DAM $\mathcal{D}$ operated in compliance with the security criterion C using $\mathcal{M}(\mathcal{S}, \mathcal{B}, \mathcal{W}; \mathcal{C})$. The problem statement explicitly takes into account all the entities that constitute the set of sellers and the set of buyers in hour h – both financial and physical players. We use the superscript $r(f)$ to denote the participants with physical resources (financial players). Therefore, the set of sellers S (buyers $\mathcal{B}$) is given by $\mathcal{S} = \mathcal{S}^r \cup \mathcal{S}^f \left(\mathcal{B} = \mathcal{B}^r \cup \mathcal{B}^f\right)$. We denote the subset with non-zero cleared quantities in the DAM by $S^{*r} \subseteq S^r$ and the subset of transactions that receive transmission services by $W^* \subseteq W$. Even though a physical buyer b^r may have $p^*_{b^r} = 0$ in $\mathcal{D}$, b^r participates in the RTM to meet his fixed demand.

Each RTM is designed to be a purely physical market restricting participation to only those players with actual loads and physical generation assets who have non-zero outcomes in the DAM. For each $\mathcal{R}|_m$, the RTO uses the offers of the physical sellers in S^{*r}, the willingness to pay of the bilateral transactions cleared in W^* and the real-time fixed demand of the physical buyers in $\mathcal{B}^r$. We use the identical system snapshot approach for $\mathcal{R}|_m$ and so we formulate and solve the market problem $\mathcal{M}(\mathcal{S}^{*r}, \mathcal{B}^r, W^*; \mathcal{C})$ for $\mathcal{R}|_m$.[2]

The metrics of interest—the auction surplus, the market participants' bid/offer surpluses and the congestion rents collected—are evaluated using the relations in Eq. 1 and Eqs. 9–11 for $\mathcal{M}(\mathcal{S}^{*r}, \mathcal{B}^r, W^*; \mathcal{C})$ for the subperiod m. We depict the inter-relationships between $\mathcal{D}$ and an associated $\mathcal{R}|_m$ in Fig. 1. We use the notation "^" to denote the optimal values attained in the clearing of $\mathcal{R}|_m$. The figure clearly

[2] Note that it is possible for a physical seller, not cleared at the DAMs, to participate in the RTMs under certain conditions. For example, the RTO may commit additional units after the clearing of the DAMs to ensure the system security in the real time. Furthermore, an RTO may also allow "self-commitment" of those resources. We do not consider these situations in the paper.

indicates the players who participate in each market, as well as the inputs and the outcomes of these markets.

The outcomes of $\mathcal{D}$ and those of $\mathcal{R}|_m$ are inputs into the settlement—the mechanism that specifies the payments to or by each market participant after the fact. We consider a system where the same MWh may be sold in two different markets—$\mathcal{D}$ and a specific $\mathcal{R}|_m$ —and so we deal with a multi-settlement system. Each of the M subperiods of the hour h has a duration of 1/M of an hour and we consider the multi-settlement for such a subperiod. A physical seller $s^r \in S^{*r}$, located at node i, who has cleared $p^*_{s^r}$ in $\mathcal{D}$ receives revenues of $1/M(\lambda^*_i p^*_{s^r})$ over that subperiod. As his real-time production $\hat{p}_{s^r}|_m$ may deviate from $p^*_{s^r}$, there is an adjustment to account for the production deviation $1/M(-p^*_{s^r} + \hat{p}_{s^r}|_m)$, which is paid at the $\mathcal{R}|_m$ LMP $\hat{\lambda}_i|_m$. The subperiod m revenues of s^r are

$$\eta_{s^r}|_m = \frac{1}{M}\left\{\lambda^*_i p^*_{s^r} + \hat{\lambda}_i\Big|_m\left(-p^*_{s^r} + \hat{p}_{s^r}|_m\right)\right\} \tag{13}$$

We note that if the seller s^r production in real time does not deviate from its DAM value, i.e. $p^*_{s^r} = \hat{p}_{s^r}|_m$, then the revenues $\eta_{s^r}|_m$ are simply the DAM revenues. As such, the $\mathcal{R}|_m$ LMP $\hat{\lambda}_i|_m$ has no impact on the subperiod m of s^r.

A financial seller s^f, located at node i, has revenues of $1/M\left(\lambda^*_i p^*_{s^f}\right)$ for his DAM "production". As s^f cannot participate in $\mathcal{R}|_m$, his real-time production $\hat{p}_{s^f}|_m = 0$, resulting in a deviation of $-p^*_{s^f}$. As a result, the RTM produces an adjustment of $-\hat{\lambda}_i|_m p^*_{s^r}$ to the DAM revenues of s^f. We may view the financial seller s^f as selling $p^*_{s^f}$ in the DAM at λ^*_i and buying back the same amount in the RTM at $\hat{\lambda}_i|_m$. The revenues of the seller s^f in subperiod m are

$$\eta_{s^f}|_m = \frac{1}{M}\left\{p^*_{s^r}\left(\lambda^*_i - \hat{\lambda}_i\Big|_m\right)\right\} \tag{14}$$

We note that as long as the DAM LMP λ^*_i is above the RTM LMP $\hat{\lambda}_i|_m$ the financial seller s^f has positive revenues.

In an analogous manner, the physical buyer b^r located at node i makes payments in the subperiod m of

$$\gamma_{b^r}|_m = \frac{1}{M}\left\{-\lambda^*_i p^*_{b^r} - \hat{\lambda}_i\Big|_m\left(-p^*_{b^r} + \hat{p}_{b^r}|_m\right)\right\} \tag{15}$$

The buyer b^r pays λ^*_i for the portion $p^*_{b^r}$ cleared in $\mathcal{D}$ and $\hat{\lambda}_i|_m$ for the remainder of his real-time demand. The payments of a financial buyer b^f in the subperiod m are

$$\gamma_{b^f}|_m = \frac{1}{M}\left\{p^*_{b^f}\left(-\lambda^*_i + \hat{\lambda}_i\Big|_m\right)\right\} \tag{16}$$

We use the same reasoning to determine the payments by the bilateral transaction $w \in W^*$ in the subperiod m to be

$$\gamma_w|_m = \frac{1}{M}\left\{\left(\lambda^*_{m_w} - \lambda^*_{n_w}\right)t^*_w + \left(\hat{\lambda}_{m_w}\Big|_m - \hat{\lambda}_{n_w}\Big|_m\right)\left(-t^*_w + \hat{t}_w|_m\right)\right\} \tag{17}$$

We note that if the bilateral transaction w does not deviate from the DAM clearing outcomes in the subperiod, then his payments are independent on the RTM outcomes.

The RTO makes the payments in Eqs. 13 and 14, to the sellers and receives from the buyers and the bilateral transactions the payments in Eqs. 15–17. The difference between these payments is the subperiod m congestion rents collected by the RTO

$$\begin{aligned} K_{\sum}\Big|_m = \frac{1}{M}&\left\{\sum_{b^r\in\mathcal{B}^r}\gamma_{b^r}|_m + \sum_{b^f\in\mathcal{B}^f}\gamma_{b^f}|_m + \sum_{w\in W^*}\gamma_w|_m\right\} \\ &- \frac{1}{M}\left\{\sum_{s^r\in\mathcal{S}^{*r}}\eta_{s^r}|_m + \sum_{s^f\in\mathcal{S}^f}\eta_{s^f}|_m\right\}. \end{aligned} \tag{18}$$

We use the results in Eqs. 13–18 for the quantification of the performance of the multi-settlement system in the subperiod m. The output of the seller $s^r \in \mathcal{S}^{*r}$ is produced in the real time, i.e. in the subperiod m, and is offered for sale for $1/M\beta_{s^r}\left(\hat{p}_{s^r}|_m\right)$. The offer surplus of the seller s^r in the subperiod m is expressed in terms of the difference between the revenues and the offer, i.e.

$$S_{s^r}|_m = \eta_{s^r}|_m - \frac{1}{M}\left\{\beta_{s^r}\left(\hat{p}_{s^r}|_m\right)\right\} \tag{19}$$

The fact that the financial seller s^f has no real-time production implies that the offer surplus of s^f equals his revenues

$$S_{s^f}|_m = \eta_{s^f}|_m \tag{20}$$

The physical buyer b^r consumes the energy in the subperiod resulting in the bid surplus given by the difference between the b^r willingness to pay in real time and the actual payments:

$$S_{b^r}|_m = \frac{1}{M}\left\{\hat{\beta}_{b^r}\left(\hat{p}_{b^r}|_m\right)\right\} - \gamma_{b^r}|_m \tag{21}$$

We note that the real time $\hat{\beta}_{b^r}$ may differ from β_{b^r} due to the fact that the real-time demand is viewed as fixed.

The financial buyer b^f cannot consume in the real time and so has the bid surplus

$$S_{b^f}|_m = -\gamma_{b^f}|_m \tag{22}$$

The bilateral transaction $w \in W^*$ receives the actual transmission service in the real time resulting in a surplus of

$$S_w\big|_m = \frac{1}{M}\left\{\alpha_w\left(\hat{t}_w\big|_m\right)\right\} - \gamma_w\big|_m \tag{23}$$

We make use of the market participants' bid/offer surpluses, including those of the bilateral transactions and the congestion rents collected by the RTO, to evaluate the total auction surplus attained in the multi-settlement system:

$$S_{\sum}\Big|_m = \sum_{s^r \in \mathcal{S}^{*r}} S_{s^r}\big|_m + \sum_{b^r \in \mathcal{B}^r} S_{b^r}\big|_m + \sum_{s^f \in \mathcal{S}^f} S_{s^f}\big|_m + \sum_{b^f \in \mathcal{B}^f} S_{b^f}\big|_m + \sum_{w \in W^*} S_w\big|_m + K_{\sum}\Big|_m. \tag{24}$$

We substitute Eqs. 18–23 into Eq. 24 to simplify and get

$$S_{\sum}\Big|_m = \frac{1}{M}\left\{\sum_{b^r \in \mathcal{B}^r} \hat{\beta}_{b^r}\left(\hat{p}_{b^r}\big|_m\right) - \sum_{s^r \in \mathcal{S}^{*r}} \beta_{s^r}\left(\hat{p}_{s^r}\big|_m\right)\right\} + \frac{1}{M}\sum_{w \in W^*} \alpha_w\left(\hat{t}_w\big|_m\right). \tag{25}$$

Now, the auction surplus attained in the RTM $\mathcal{R}_m$ is $\hat{S}\big|_m$ and its value is given by Eq. 1:

$$\hat{S}\Big|_m = \frac{1}{M}\left\{\sum_{b^r \in \mathcal{B}^r} \hat{\beta}_{b^r}\left(\hat{p}_{b^r}\big|_m\right) - \sum_{s^r \in \mathcal{S}^{*r}} \beta_{s^r}\left(\hat{p}_{s^r}\big|_m\right)\right\} + \frac{1}{M}\sum_{w \in W^*} \alpha_w\left(\hat{t}_w\big|_m\right). \tag{26}$$

We conclude that

$$S_{\sum}\Big|_m = \hat{S}\Big|_m. \tag{27}$$

Therefore, the total auction surplus of the multi-settlement system attained in the subperiod m is precisely the auction surplus attained in $\mathcal{R}\big|_m$. We, furthermore, conclude that the outcomes of $\mathcal{D}$ do not explicitly impact the total auction surplus. $S_{\sum}|_m$, but impact the allocation of the total auction surplus among the market participants.

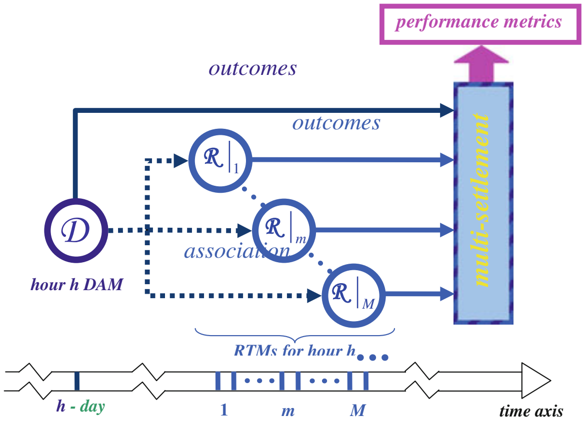
The performance metrics in Eqs. 18–25 are for the subperiod m of the hour h. We aggregate them for the M subperiods of hour h to evaluate the hourly metrics. In particular, we compute the hour h auction surplus $S_{\sum}$ attained in the multi-settlement system to be

$$S_{\sum} = \sum_{m=1}^{M} S_{\sum}\Big|_m = \sum_{m=1}^{M} \hat{S}\Big|_m \tag{28}$$

The performance quantification of the multi-settlement system clearly makes use of the inter-relationships between the DAM and its associated RTMs, as illustrated in Fig. 2.

We note the clearing of the financial entities in $\mathcal{D}$ impacts the clearing of the physical generation as well as the clearing of the physical loads. As such, the participation of the financial entities impacts the deviations of the physical resources clearing in the real time. Such deviations have implications on the

Fig. 2 Interactions between $\mathcal{D}$ and $\mathcal{R}|_m$ and the performance quantification in a multi-settlement environment



market and the system operations. In particular, they impact the ability of the RTO to ensure real-time system security.

We also note that a single-settlement system is a special case of multi-settlement systems. An example of such a case is that every transaction at the DAM corresponds to physical production and the DAM clearing perfectly forecasts real-time system conditions, as such no net injection deviation at each node in real time. Under such conditions, the clearing of the DAMs or their associated RTMs represents a single-settlement system.

In the next section, we describe the proposed approach to quantitatively assess the impacts of operating a system under a specified criterion C on the market performance in a multi-settlement environment. Also, we quantify the impacts of financial entities on the ability of the RTO to meet system security C in the near-real-time.

4 Proposed Approach

The maintenance of secure power system operations is a task that strongly depends on the outcomes of the DAMs. We may view the DAM physical generation and consumption as a rough guess of the actual outcomes in the associated RTMs. As the system and the market conditions in the near to real time may change from those forecast and cleared in the DAM, the RTMs are run to manage the resulting deviations.

The actual physical demand in the M RTMs gives rise to the physical demand deviation in hour h:

$$\delta \hat{p}_{\mathcal{B}^r} = \frac{1}{M} \left[\sum_{m=1}^{M} \left(\sum_{b^r \in \mathcal{B}^r} \hat{p}_{b^r}|_m + \sum_{w \in W^*} \hat{t}_w|_m \right) \right] - \left[\sum_{b^r \in \mathcal{B}^r} p^*_{b^r} + \sum_{w \in W^*} t^*_w \right] \tag{29}$$

A non-zero $\delta\hat{p}_{\mathcal{B}^r}$ indicates that the physical buyers' DAM purchases are either below or above the consumption in real time. Similarly, the physical generation deviation in hour h is

$$\delta\hat{p}_{\mathcal{S}^{*r}} = \frac{1}{M}\left[\sum_{m=1}^{M}\left(\sum_{s^r\in\mathcal{S}^{*r}}\hat{p}_{s^r}|_m + \sum_{w\in W^*}\hat{t}_w|_m\right)\right] - \left[\sum_{s^r\in\mathcal{S}^{*r}}p^*_{s^r} + \sum_{w\in W^*}t^*_w\right]. \tag{30}$$

The participation of the financial entities in the DAM gives rise to the lack of balance between physical demand deviation $\delta\hat{p}_{\mathcal{B}^r}$ and the physical generation deviation $\delta\hat{p}_{\mathcal{S}^{*r}}$. A positive net injection of the financial participants in the DAM corresponds to $\sum_{s^f\in\mathcal{S}^f}p^*_{s^f} > \sum_{b^f\in\mathcal{B}^f}p^*_{b^f}$, which implies that $\sum_{s^r\in\mathcal{S}^{*r}}p^*_{s^r} < \sum_{b^r\in\mathcal{B}^r}p^*_{b^r}$. In this case, the physical generation deviation exceeds the physical demand deviations so that $\delta\hat{p}_{\mathcal{S}^{*r}} > \delta\hat{p}_{\mathcal{B}^r}$. Therefore, more generation is required in real time than cleared in $\mathcal{D}$ leading to the deviations in the physical sellers' outcomes. In case of $\sum_{s^f\in\mathcal{S}^f}p^*_{s^f} < \sum_{b^f\in\mathcal{B}^f}p^*_{b^f}$ —a negative net injection of the financial entities—some of the physical generation serves the demand of the financial buyers in $\mathcal{D}$ and so $\sum_{s^r\in\mathcal{S}^{*r}}p^*_{s^r} > \sum_{b^r\in\mathcal{B}^r}p^*_{b^r}$. In this case, $\delta\hat{p}_{\mathcal{S}^{*r}} < \delta\hat{p}_{\mathcal{B}^r}$. Whenever there is zero net injection by the financial entities, the physical generation deviation and the physical demand deviation are in exact balance. The absence of financial entity participation is a special case of this zero net injection. While the injection/withdrawal deviation metrics of Eqs. 29 and Eqs. 30 provide system-wide aggregate measures, we can also introduce analogous metrics for zonal, as well as, nodal measures in order to meet the requirements at the different levels of granularity.

We use the auction surplus in Eq. 28, the total congestion rents in Eq. 18 and each market participants' bid/offer surplus metric in Eqs. 19–23 to evaluate the overall economic performance of the multi-settlement system and that of each market participant, respectively. In addition, we need appropriate metrics to analyze the combined impacts of the DAM-RTM clearing outcomes.

As market and system conditions may change, the price of the MWh commodity in each $\mathcal{R}|_m$ at a specified node may deviate from that in $\mathcal{D}$. The hour h price deviation at node i is

$$\delta\lambda_i = \frac{1}{M}\sum_{m=1}^{M}\left[\lambda^*_i - \hat{\lambda}_i\Big|_m\right]. \tag{31}$$

Whenever $\delta\lambda_i \neq 0$ over a nontrivial subset of hours, arbitrage opportunities exist, implying market inefficiency [26]. A financial entity can participate in the market to take advantage of price arbitrage opportunities at such a node. As more and more financial entities eye such opportunities, leading to their participation in the markets to arbitrage the price deviation, the arbitrage opportunities begin disappearing. As such, $\delta\lambda_i \to 0$, leading to the improved economic efficiency of the markets. Thus, price convergence is a desirable outcome in multi-settlement systems. We also note that $\delta\lambda_i - \delta\lambda_j$, $i \neq j$, quantifies how well the $\mathcal{D}$ outcomes forecast the nodal price difference between nodes i and j in real time taking into account the actual system congestion and losses.

The price deviation $\delta\lambda_i$ also impacts the surplus of each market participant. The output of the seller $s^r \in \mathcal{S}^{*r}$, located at node i, is produced in the real time. Therefore, his offer is, unlike his revenues in Eq. 13, independent of the $\mathcal{D}$ outcomes. Therefore, the $\mathcal{D}$ outcomes impact the surplus of the seller s^r in hour h. Using Eq. 19, the s^r offer surplus in hour h is

$$\mathcal{S}_{s^r} = \frac{1}{M}\sum_{m=1}^{M}\left\{\hat{p}_{s^r}|_m \hat{\lambda}_i\Big|_m - \beta_{s^r}\left(\hat{p}_{s^r}|_m\right)\right\} + \delta\mathcal{S}_{s^r} \tag{32}$$

Here, $\delta\mathbf{S}_{s^r}$ is the physical seller offer surplus deviation metric

$$\delta\mathbf{S}_{s^r} = p^*_{s^r}\delta\lambda_i \tag{33}$$

and quantifies the impact of the $\mathcal{D}$ outcomes on the revenues of the seller s^r. A positive (negative) $\delta\mathcal{S}_{s^r}$ implies that s^r captures more (less) revenues for his real-time production than those in $\mathcal{D}$. We consider a specific case to illustrate the nature of $\delta\mathcal{S}_{s^r}$. For a system with s^r, the marginal seller in both $\mathcal{D}$ and an associated $\mathcal{R}|_m$ and with $\hat{\lambda}_i|_m > \lambda^*_i$ and $\hat{p}_{s^r}|_m > p^*_{s^r}$. While $p^*_{s^r}$ is paid at λ^*_i the $\hat{p}_{s^r}|_m - p^*_{s^r}$ is paid at $\hat{\lambda}_i|_m$. Therefore, the portion $p^*_{s^r}$ receives less revenues per MWh than $\hat{p}_{s^r}|_m - p^*_{s^r}$. The fact that s^r participates in $\mathcal{D}$ and sells $p^*_{s^r}$ implies that for this case he receives lower revenues than had he participated in only $\mathcal{R}_m$. As such, s^r is better off clearing a lesser amount than $p^*_{s^r}$ whenever $\hat{\lambda}_i|_m > \lambda^*_i$ so as to increase revenues for its actual production $\hat{p}_{s^r}|_m$. The negative δS_{s^r} is illustrated in Fig. 3. Whenever a financial buyer b^f realizes such a price deviation, then his participation in $\mathcal{D}$ that may result in an increase in λ^*_i. In turn, the revenues of s^r may increase and he may be willing to produce more in $\mathcal{D}$ than in the case of without the financial buyer b^f. We note that the surplus driven offer/bid decisions furthermore impact the

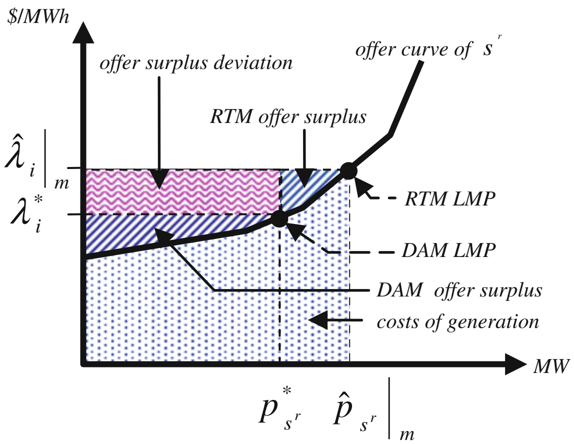


Fig. 3 The effects of $\mathcal{D}$ and $\mathcal{R}|_m$ clearing on the offer surplus deviation of the physical seller s^r located at node i for the case $\hat{\lambda}_i|_m > \lambda^*_i$

deviation of the physical production/consumption. Under the conditions of the example, as the physical seller has the incentive to clear a lesser amount in $\mathcal{D}$ due to the price deviation, the need may arise for additional amounts cleared in the near-real-time. We conclude that such incentives may result in conditions that the ‘physical production/consumption in $\mathcal{D}$does not appropriately forecast the real-time conditions, and may lead to “stressed” real-time operations, thereby lessening the ability to ensure secure power system operations.

Once we compute the individual offer surplus deviation of a physical seller, we can determine the offer total surplus deviation of the subset of the physical sellers using

$$\delta\mathcal{S}_{\mathcal{S}^{*r}} = \sum_{i=0}^{N} \sum_{s^r \in \mathcal{S}^{*r}} p^*_{s^r} \delta\lambda_i \varepsilon_{is^r}, \varepsilon_{is^r} = \begin{cases} 1, & s^r \textit{ is at node } i \\ 0, & \textit{otherwise} \end{cases} \tag{34}$$

Similarly, we can evaluate the total physical buyers’ bid surplus deviations

$$\delta\mathcal{S}_{\mathcal{B}^{r}} = \sum_{i=0}^{N} \sum_{b^r \in \mathcal{B}^{r}} p^*_{b^r} \delta\lambda_i \varepsilon_{ib^r}, \varepsilon_{ib^r} = \begin{cases} 1, & b^r \textit{ is at node } i \\ 0, & \textit{otherwise} \end{cases} \tag{35}$$

A positive $\delta S_{\mathcal{B}^r}$ implies that the physical buyers pay less for their aggregate real-time demand in $\mathcal{D}$ than in the associated RTMs. This happens because the physical buyers benefit from the lower DAM prices that they pay for the portion of the demand cleared in the DAM.

The MW deviation metrics along with the price and the bid/offer surplus deviation metrics capture important aspects of system and market operations in a multi-settlement environment. The physical generation and demand deviation metrics quantify how “close” the real-time system conditions are to those forecasted in the clearing of the DAM. Smaller magnitude deviations imply improved “forecasts” of the system conditions in the DAM, which, in turn, result in the improved ability of the RTO to ensure real-time system security. Therefore, the DAM clearing is strongly inter-related with the real-time system operations. The price and the physical participants’ bid/offer surplus deviation metrics, on the other hand, quantify the impacts of the DAM outcomes on the market participants’ bid/offer surpluses. As price deviations increase, the financial entity participation becomes more pronounced in the DAMs [26, 27]. Such participation leads to changes in the DAM outcomes, which, in turn, impact how the real-time system conditions are forecasted in the DAM. A desirable market outcome is that the deviation metrics of surplus and of production/consumption tend to zero since the lower the absolute values of these metrics, the “better” the markets perform. The ability to quantify the economic impacts of compliance with a specified security criterion renders these metrics highly appropriate in the preparation of various regulatory filings, as well as in applications to longer-term planning and shorter-term studies with the explicit representation of the financial entities in addition to the physical asset owners. The proposed metrics capture the strong inter-relationships between system and market operations in the multi-settlement

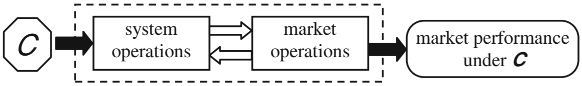


Fig. 4 The market performance quantification under security criterion C

environments. Therefore, they effectively quantify the performance of the multi-settlement systems.

The value of the metrics given in Eqs. 9–35 depends on the specified security criterion C and constitutes the basic building of the approach. We conceptually represent this snapshot assessment framework in Fig. 4.

Under a different security criterion $C^{'}$, the RTO explicitly considers the solution of the problem $\mathcal{M}(S, \mathcal{B}, W; C')$ at each system snapshot, be it a DAM or an RTM. The constraints expressed in Eqs. 2–8 apply to each contingency in the set $J_{C'}$. We measure the impacts on market performance due to the change in the security criterion from C to $C^{'}$ by the change in each metric of interest from one criterion to the other. For example, the change in the auction surplus metric is given by

$$\Delta S_{\sum}\Big|_{C \rightarrow C'} = S_{\sum}\Big|_{C'} - S_{\sum}\Big|_{C} \tag{36}$$

and provides a proxy measure for the change in the economic efficiency of the markets in a multi-settlement environment due to a change in the security criterion from C to $C^{'}$. We deploy analogous expressions for each metric in Eqs. 9–35 to measure the relative change in response to the security criterion change from C to $C^{'}$. The changes in the bid/offer surpluses, the total dispatched load and the multi-settlement system deviation metrics are all of interest in our assessment. We also need the changes in the physical demand and generation deviation to quantify the impacts on the ability of the RTO to meet system security in real time. For example, to evaluate the impacts on the physical generation deviation, we use

$$\Delta\delta_{S^{*}r}|_{C \rightarrow C'} = \delta\hat{p}_{S^{*r}}|_{C'} - \delta\hat{p}_{S^{*r}}|_{C} \tag{37}$$

These metrics effectively capture the multi-settlement system performance for the security criterion change from C to $C^{'}$ for a given hour h. For example, the RTO can quantify the economic impacts of operating the system under a tightened security criterion by including additional contingencies in the postulated contingency list.

Under a specified security criterion, the hourly snapshots corresponding to different system and market conditions may result in markedly different market performance outcomes. Such differences arise for many reasons including changes in the load, the set of selling entities, and the offers/bids submitted. Consequently, these hourly assessments must be carried out over a longer period to appropriately capture the impacts of the different conditions that exist during that period. Conceptually, we need to assess the market performance of the DAM and the associated RTMs at each hour of the study period. The needs are similar in assessing the market performance impacts due to a change in the security criterion. The hourly values of the relative performance metrics are summed to obtain the daily values which, in turn, are used to compute the relative performance metrics for the entire study period. As the computing requirements to clear each market over a study period for a large-scale system may be large, a practical way to reduce them is to perform the assessments for a smaller representative sample of the hours. For this purpose, we require a scheme that systematically selects this smaller subset of representative hours [33].

A key requirement in selecting these hours is the incorporation of the unit commitment decisions which entail inter-temporal effects across the hours of the commitment. To fully capture the inter-temporal effects, all the hours of the unit commitment period need to be considered. Since, for typical market applications, the unit commitment period is a day, this requirement shifts the selection of representative sample of hours to that of days, since all the hours of such days must be included.

A first step in the selection of representative days is the partitioning of the study period into subperiods. Since many operational studies are carried out on a monthly basis, we use a month as a subperiod. For a given month i, we determine the subset of representative days and construct the set D_r^i using the following scheme.

Let $D^i = \{d_q : q = 1,\ldots, D\}$ be the set of days in the month i. We denote the day d_q peak-demand load by p_{d_q}. We reorder the set of the demand values $\{p_{d_1}, \ldots, p_{d_D}\}$ as $\{\tilde{p}_1, \ldots, \tilde{p}_D\}$ with $\tilde{p}_j \geq \tilde{p}_{j+1}$ where $\tilde{p}_j$ denotes the jth largest value of the month. We construct the ordered daily load curve using the set of points $\{(0, \tilde{p}_1), (1, \tilde{p}_2), \ldots, (D-1, \tilde{p}_D)\}$. This curve has at most D distinct load levels. We normalize the time axis using D as the base value and construct the so-called load duration curve (*LDC*)$L(\cdot)$ as a piece-wise step function using the set of points $\{(0, \tilde{p}_1), (1/D, \tilde{p}_2), \ldots, ((D-1)/D, \tilde{p}_D)\}$. We super-pose the grid with k equally distributed LDC factors

$$0 = \psi_0 < \psi_1 < \cdots < \psi_{k+1} = 1 \tag{38}$$

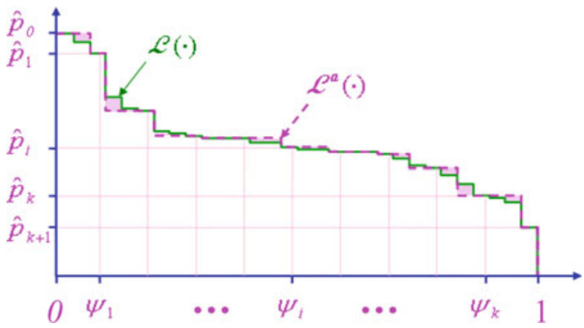
on the time axis. We determine the load level $\hat{p}_j = L(\psi_j)$ for each ψ_j. We choose k so that the $(k+2)$ load values are distinct and

$$\hat{p}_0 > \hat{p}_1 > \cdots > \hat{p}_{k+1} \tag{39}$$

We use the load levels to subdivide the interval between $\hat{p}_0$ and $\hat{p}_{k+1}$ into $(k+2)$ load tranches

$$P_j = \begin{cases} \left[\hat{p}_{k+1}, \dfrac{\hat{p}_k + \hat{p}_{k+1}}{2}\right] & j = k+1 \\ \left(\dfrac{\hat{p}_{j-1} + \hat{p}_j}{2}, \dfrac{\hat{p}_j + \hat{p}_{j+1}}{2}\right] & j = 1, \ldots, k \\ \left(\dfrac{\hat{p}_0 + \hat{p}_1}{2}, \hat{p}_0\right] & j = 0 \end{cases} \tag{40}$$

Fig. 5 Construction of $L^a(\cdot)$ from $L(\cdot)$



and determine from the time axis the corresponding duration n_j of each tranche. Note that n_j is an integer multiple of $1/D$ and $\sum_{j=0}^{k+1} n_j = 1$. We define

$$\hat{\psi}_j = \sum_{s=0}^{j-1} n_s,\ j = 1, \ldots, k. \tag{41}$$

We construct $L^a(\cdot)$ from the $(k+2)$ load levels using the set of points $\{(0,\hat{p}_0),(\hat{\psi}_0,\hat{p}_1),\ldots,(\hat{\psi}_k,\hat{p}_{k+1})\}$ and use it to approximate $L(\cdot)$. For each load level $\hat{p}_j$ of $L^a(\cdot)$, we identify the day d_q with $p_{d_q} = \hat{p}_j$. In case of two or more such days, we select the most or more recent day. We construct D_r^i using these $(k+2)$ selected days. We illustrate such construction in Fig. 5.

We measure the "goodness" of the approximation in terms of an error based on the monthly energy. We define the error in the LDC approximation by

$$\varepsilon(k) = \int_0^1 |L^a(x;k) - L(x)|dx \Bigg/ \int_0^1 L(x)dx \tag{42}$$

We compare the value of $\varepsilon(k)$ with a specified error tolerance value $\bar{\varepsilon}$. If the error fails to satisfy $\bar{\varepsilon}$,k is increased until the tolerance check is satisfied and selects the corresponding D_r^i.

We repeat this process for each of the month within the study period and then construct the set of representative days $\boldsymbol{D}_r$ of the study period by the union of the monthly D_r^i. We apply the structure shown in Fig. 4 to each hour of the days in $\boldsymbol{D}$ for each specified criteria. We quantify the hourly relative performance metrics and aggregate them for each day. We use the number of days each day in D_r^i represents and aggregate the daily figures to obtain monthly impacts. The daily figures also serve to evaluate key statistics for each month such as mean, variance and range. The study period impacts then are aggregated form the monthly ones. Thus, we are able to quantify the system and area-wide MW as well as dollar impacts on a daily, monthly and period basis.

The proposed approach provides a useful tool to the RTO to analyze the interdependence between market performance and the system security. The ability to quantify the financial impacts of compliance with a specified security criterion makes the approach highly useful in regulatory proceedings, as well as in longer-term planning and shorter-term investigations with the explicit representation of both the financial and the physical asset owning players. The proposed approach has a wide range of applications such as the justification by the RTO of the decision to modify the security criterion to be used and the cost/benefit analysis of network improvements to mitigate the market performance impacts of a set of specified contingencies. Other applications include the formulation of the control actions for specific contingencies, and the assessment of specific behavioral changes of market participants under various security criteria. The proposed approach furthermore allows us to investigate the role of the DAMs in reallocating the auction surplus among market participants, to analyze the DAM–RTM price deviation issues and to quantify the impacts of the financial entities participation on real-time system security. We devote the following section to present a set of applications to the large-scale ISO New England (ISO-NE) of the proposed approach.

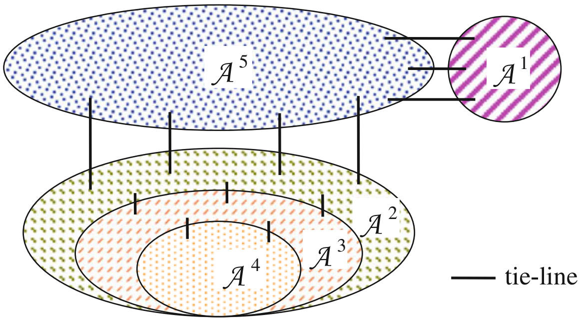
5 Application Studies: The ISO-NE System

In this section, we provide a set of application studies to quantify the economics of secure power system operations for the ISO-NE markets for the case of DAMs only, as a proxy study for single-settlement systems, and for the multi-settlement system. We use the ISO-NE in all the case studies presented since it provides a good, realistic-sized system that is large enough to effectively illustrate the capabilities of the proposed approach to determine practical solutions to a wide range of problems in the various applications. We, first, provide a brief description of the multi-area structure of the ISO-NE system and state the current ISO-NE security criterion. We, next, provide the results of the ISO-NE DAM comparative study and those of the set of studies for the multi-settlement system.

The ISO-NE is the regional transmission organization serving the states of Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island and Vermont. The ISO-NE is a member of the Northeast Power Coordinating Council (NPCC) and is part of the Eastern Inter-connection. An important characteristic of the ISO-NE system is its multi-area structure. Such a structure has major implications for the way the system operations comply with the security criterion. Each area of the ISO-NE multi-area network is characterized as being either an import or an export area. We depict conceptually the multi-area structure of the ISO-NE in Fig. 6. The import areas [34] are

- A^1: Boston/NE Massachusetts
- A^2: Connecticut

Fig. 6 Multi-area structure of the ISO-NE system



- A ^{3}: SW Connecticut
- A ^{4}: Norwalk/Stamford

We treat rest of the system as a single export area and denote it by $A^{\cdot 5}$. Figure 2 illustrates conceptually the multi-area structure of the ISO-NE. A salient feature is the nested structure of the areas $A^{\cdot 4} \subset A^{\cdot 3} \subset A^{\cdot 2}$. From the physical and the economic point of view, the generation of the export area is required to meet the load of the import areas.

The ISO-NE system security criterion takes into account this multi-area structure. This is a modified (n – 2) security criterion. We denote this security criterion by $\mathbf{C}_0$, whose contingency list is $J_{C_0}=J_{n-1} \cup \left(\bigcup_{k=1}^{4} M^k\right)$. Here, $\boldsymbol{J}_{n\text{-}1}$ is the set of single element contingencies considered by the ISO-NE and $\boldsymbol{M}^k$ is the set of double tie line contingencies specified for each import area A $^k \in$ A, k=1,…,4. Each selected tie line pair interconnects the import area A ^{k} to any other area of the system. The set of control actions for the security criterion consists of preventive control actions which are associated with the elements of $\boldsymbol{J}_{n\text{-}1}$, and corrective control actions which are associated with the double element tie line contingencies of $\bigcup_{k=1}^{4} M^k$[34].

We next focus on the studies to quantify the economics of secure power system operations in the ISO-NE system. The objective of this study is to analyze whether the economic efficiency of the ISO-NE DAM is adversely impacted by the system operations complying with the security criterion in force.[3] For this purpose, we quantify the market performance as a function of three security criteria and perform comparative assessments. We measure the changes with respect to the outcomes under the current ISO-NE security criterion. We quantify the impacts of the security criterion in force on the market performance using the actual day-ahead data – the system model and the bids/offers submitted—with the actual market

[3] We use the ISO-NE DAM study as a proxy study for single-settlement systems. We assume that the bids and the offers of the financial entities represent physical consumption and production. As such, this study is a special case for multi-settlement systems. .

clearing methodology. The results of this study serve as the reference case, with respect to which we compare the impacts of a tightened and a relaxed security criterion on the market performance.

We select the criterion $\mathbf{C}_0$ as the reference criterion and consider two specific criteria C_1 a modified (n–1) security, and C_2, a modified (n – 2) security. For the criterion C_1, the contingency list $J_{C_1} = J_{n-1}$, and preventive control action is the deployed for each contingency in J_{C_1}. For the criterion C_2, the contingency list $J_{C_2} = J_{C_0}$, but we replace the corrective control actions by the preventive control actions for the contingencies in $\overset{4}{\underset{k=1}{\cup}} M^k$.

The study is performed for the second half of the year 2005. This study period was chosen to allow the use of market and system data that reflects the most up-to-date ISO-NE procedures and rules. The analysis of the load in the selected period shows that the demand levels in the summer months, July and August, are significantly higher than those in the non-summer months—the months from September to December. Furthermore, the range of daily peak demands in the summer months is considerably larger than that in the non-summer months. Due to the maintenance scheduling, the sets of available resources in summer months are different than those in the other months. In addition, the ratings of the system components differ in each summer month from those in the other months. The period under study is further characterized by the existence of two distinct regimes, $\mathcal{R}_1$ and $\mathcal{R}_2$ (pre- and post-October 9, 2005), respectively. The ratio of the hourly price-sensitive bid amounts to the total hourly demand changes markedly from a small value under the regime $\mathcal{R}_1$, to a sizable fraction under the regime $\mathcal{R}_2$. The hourly loads in these two regimes are further distinguished in terms of their peak, base and average values. We present the load characteristics of the regimes $\mathcal{R}_1$ and $\mathcal{R}_2$ in Table 1. The minimum, maximum and the average hourly load values are disaggregated into the fixed and price-responsive components in Table 1. The significant increase in the fraction of price-sensitive demand is due to the bidding behavior change of the large buying entity whose demand corresponds to approximately 25% of the total system demand. This buyer submits, on the average, only 10% of his demand as price-sensitive under the regime $\mathcal{R}_1$. However, the buyer has no fixed demand under regime $\mathcal{R}_2$ as the entire buyers' bids become price-sensitive, as shown in Fig. 7. Due to the size of the buyer's demand, the marked change in his bidding behavior results in a significant portion of the total system demand that is price responsive under the regime $\mathcal{R}_2$.

Table 1 Regimes $\mathcal{R}_1$ and $\mathcal{R}_2$ load characteristics

Regime	$\mathcal{R}_1$		$\mathcal{R}_2$	
Load type	Fixed	Price-sensitive	Fixed	Price-sensitive
Minimum demand	6,232	2,944	5,394	5,139
Maximum demand	21,292	4,845	12,109	9,573
Average	13,075	4,294	8,756	6,964

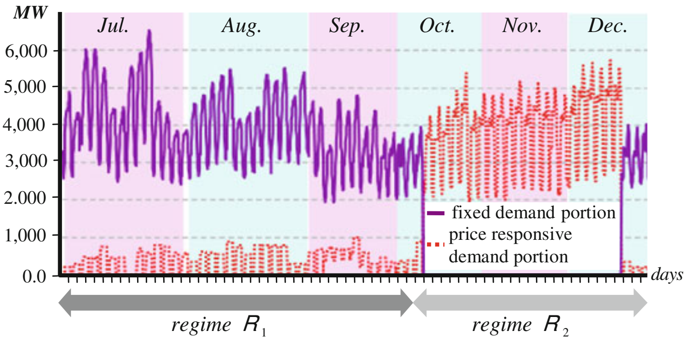


Fig. 7 The bidding behavior change of the larger buying entity

We select the representative days from each month using the scheme introduced in the previous section. We construct the LDC approximation for each summer and non-summer month by 14 and 10 representative days, respectively. Since these approximations provide acceptably small errors, we determine the elements of each D_r^i and construct $\mathcal{D}_r$.

We next discuss the market performance impacts of the change of security criterion $\mathbf{C}_0$ to each of the criteria considered and distinguish those impacts under the two regimes $\mathcal{R}_1$ and $\mathcal{R}_2$

We first focus on the MW impacts. For the reference criterion $\mathbf{C}_0$, we obtain the range and the average values of the total hourly dispatched load P_C under the regimes $\mathcal{R}_1$ and $\mathcal{R}_2$. We compute the changes from the P_C values under the two security criteria and present the results in Table 2. We observe that the price-responsive demand plays an important role in the DAM. For each security criterion, the changes under the regime $\mathcal{R}_2$ are considerably lower than those under the regime $\mathcal{R}_1$. In fact, the changes are more pronounced for the change of the security criterion from $\mathbf{C}_0$ to C_2 than from $\mathbf{C}_0$ to C_1. We hypothesize that the factors that contribute to these distinct outcomes are due to the structure of the system, the effectiveness of the security control actions and the nature of the constraints imposed on the system operations.

The change from the current security criterion to either of the two criteria studied impacts the value of the system transfer capability. The change in the value of the system transfer capability, in turn, affects the ability of the import areas to

Table 2 Total hourly dispatched loads and range of impacts

Metric	Regime	Range (MW)	Average (MW)
$P_{\mathbf{C}_0}$	$\mathcal{R}_1$	(9,177, 25,638)	16,967
	$\mathcal{R}_2$	(8,733, 23,281)	15,421
ΔP_{C^a}	$\mathcal{R}_1$	(0, 452)	141
	$\mathcal{R}_2$	(0, 273)	42
ΔP_{C^b}	$\mathcal{R}_1$	(−818, 0)	−184
	$\mathcal{R}_2$	(−557, 0)	−128

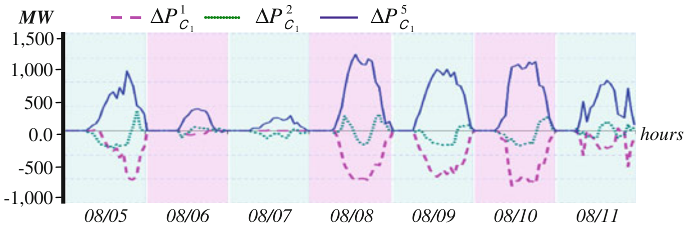


Fig. 8 Area-wide net injection impacts under C_1

bring in energy from the export area. In fact, the analysis of the ISO-NE system during this 2005 study period indicates that the replacement of the security criterion $\mathbf{C}_0$ by the criterion C_1 results in the increased import capabilities of the import areas for each hour. But, the increased capability may not be utilized in every hour. For example, the imports by the stand-alone area $\mathcal{A}^1$ buyers increase their imports from the export area, thereby decreasing their dependence on the less economic $\mathcal{A}^1$ resources. On the other hand, the imports of the nested area $\mathcal{A}^2$, due to the physical constraints of the $\mathcal{A}^2$ network, may not utilize such increased capability in every hour. We measure the changes in the utilization of the increased import capabilities using the relative area-wide net injection metric for the areas $\mathcal{A}^1$, $\mathcal{A}^2$ and $\mathcal{A}^5$. We illustrate the results for the import areas $\mathcal{A}^1$ and $\mathcal{A}^2$, and the export area $\mathcal{A}^5$ for a week in August 2005 in Fig. 8. These plots are typical for the study period, particularly in terms of the more pronounced impacts in the daily peak hours than those in the off-peak hours.

Due to the fact that the system operations under the criterion C_2 are more constraining than those under the criterion $\mathbf{C}_0$, the security change from $\mathbf{C}_0$ to C_2 results in the decreased import capabilities of the import areas for every hour of the study period. In fact, the impacts on the imports of the stand-alone area $\mathcal{A}^1$ are exactly in the opposite direction to those under the criterion change from $\mathbf{C}_0$ to C_1. On the other hand, the imports of the nested area $\mathcal{A}^2$ exhibit similar results to those under the criterion change from $\mathbf{C}_0$ to C_1. We plot these outcomes for the same August week in Fig. 9. We note that the impacts are pronounced in both peak and off-peak hours.

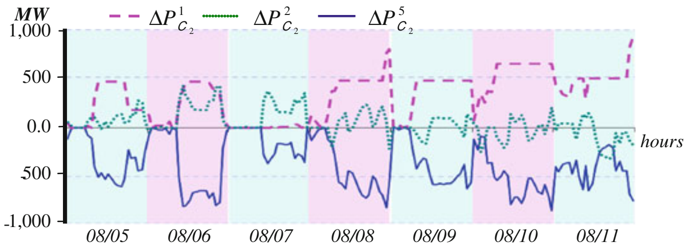


Fig. 9 Area-wide net injection impacts under C_2

We next examine the monetary impacts of the changes in the security criterion as measured by the relative auction surplus metric. We use the daily auction surplus as the basic metric in this investigation. We first normalize the daily auction surplus values using the average value of the daily auction surplus under the reference criterion $\mathbf{C}_0$ as a base value. We use the normalized values to compare the impacts with respect to the values under the reference criterion, as well as, across study periods of different durations. In this way, the comparisons are both consistent and meaningful. We can interpret the results to understand the nature of the impacts and how they relate to the values attained under the reference criterion $\mathbf{C}_0$. For concreteness, we use a value of $\tau = 1{,}000$ \$/MWh/h for evaluating the benefits of the buyers submitting fixed demand. We first consider the economic repercussions of the increased import capabilities arising from the relaxation of the security criterion from $\mathbf{C}_0$ to C_1. Throughout the study period, the increased import capabilities are utilized leading to higher market efficiencies. We may view these improvements as a measure of the "costs" of not violating the constraints due to the double element contingencies in the reference criterion. On the other hand, the decreased import capabilities arising from changing the criterion from $\mathbf{C}_0$ to C_2 may lower the auction surplus. Indeed, such reductions are present throughout the study period. We may interpret these reductions to be a measure of the "costs" of replacing corrective for preventive control actions. The plot of the normalized daily auction surplus values under the reference criterion $\mathbf{C}_0$ is given in Fig. 10 for the set of days $\mathcal{D}^r$. The plots of the changes in auction surplus arising from a change of the security criterion are shown in Fig. 11. In this figure, we also provide the normalized impacts considering a different value of $\tau' = 10{,}000$ \$/MWh/h. Note that, the different values of τ and τ' impact the normalized values but do not affect the nature of the impacts. We provide some of the statistics related to the maximum, the mean and the standard deviation of the values of relative auction surplus metrics under the regimes $\mathcal{R}_1$ and $\mathcal{R}_2$ for each security criterion change in Table 3.

We obtain additional insights into the impacts of the security criterion change on the market participants in each area by studying the disaggregation of the

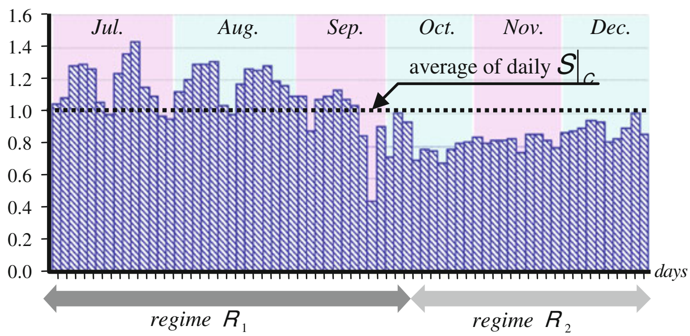


Fig. 10 Normalized daily auction surplus under criterion $\mathbf{C}_0$

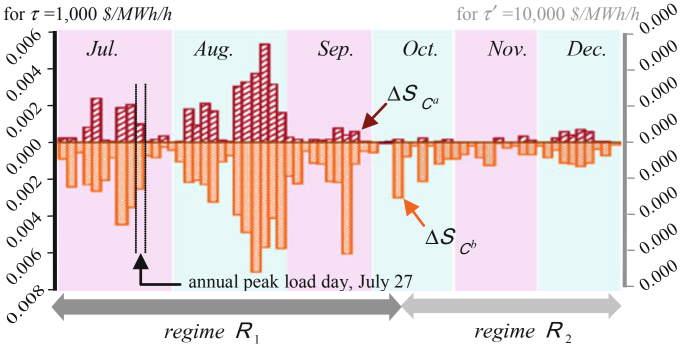


Fig. 11 The normalized daily impacts on auction surplus

Table 3 Statistical analysis of the relative auction surplus metric values under the regimes $\mathcal{R}_1$ and $\mathcal{R}_2$ (basis is $\mathbf{C}_0$)

Criterion	Regime	Maximum	Mean	SD
$\mathbf{C}_1$	$\mathcal{R}_1$	0.00541	0.00098	0.00130
	$\mathcal{R}_2$	0.00070	0.00012	0.00023
$\mathbf{C}_2$	$\mathcal{R}_1$	−0.00715	−0.00224	0.00182
	$\mathcal{R}_2$	−0.00215	−0.00068	0.00051

metrics $\Delta S|_{\mathbf{C}_0\rightarrow\mathbf{C}_1}$ and $\Delta S|_{\mathbf{C}_0\rightarrow\mathbf{C}_2}$. The area by area contribution is in line with the changes in the utilization of the modified import/export capabilities. We plot the changes of the import areas $\mathcal{A}^1$ and $\mathcal{A}^2$, and the export area $\mathcal{A}^5$, contribution to the auction surplus in Fig. 12 (Eq. 13) corresponding to shifting the security criterion from $\mathbf{C}_0$ to $\mathbf{C}_1$ ($\mathbf{C}_2$).

The price-responsive demand that characterizes regime $\mathcal{R}_2$ plays an important role in the nature of the results. In general, as the willingness to pay of the buyers increases, the absolute value of the relative auction surplus metric increases, attaining its highest value for fixed demand for each security criterion considered.

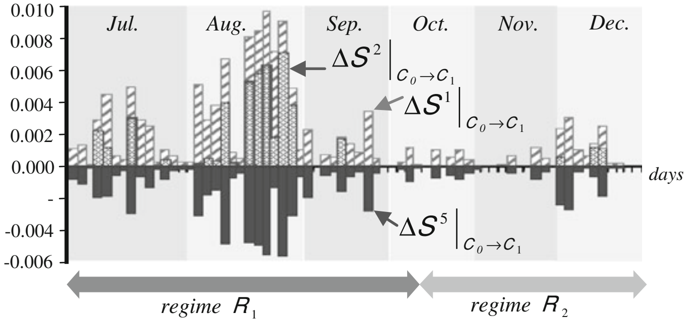


Fig. 12 Change in each area's contributions to auction surplus under $\mathbf{C}_1$

Therefore, the impacts of the change in security criterion to either $\mathbf{C}_1$ or $\mathbf{C}_2$ on the auction surplus are more pronounced for the fixed demand regime $\mathcal{R}_1$ than for the price-responsive regime $\mathcal{R}_2$, as we observe in the plots of Figs. 10, 11, 12, 13. Also, for a price-responsive demand with a uniformly low willingness to pay, the impacts may be small, and in certain cases may be negligibly so. The relaxation of the security criterion from $\mathbf{C}_0$ to $\mathbf{C}_1$ by not taking into account the double element contingencies, results in an insignificantly small relative auction surplus metric values under the regime $\mathcal{R}_2$. The tightening of the security criterion from $\mathbf{C}_0$ to $\mathbf{C}_2$ using preventive actions to replace corrective ones reduces the auction surplus. In fact, by utilizing the corrective control capabilities of the resources in the presence of price-responsive demand, the ISO-NE is able to decrease the economic impacts of the double tie line contingencies. Note that the extent of such ability depends on various factors including the topology of the system, the characteristics of the generating units and the bids/offers of the market participants.

These findings of the comparative assessment lead us to conclude that the reference criterion $\mathbf{C}_0$ is, for all intents and purposes, more appropriate for the ISO-NE DAM than either of the two security criteria considered. Through this study, we also gain important insights on the role of price-responsive demand and the selected security control action. In fact, a key finding of the ISO-NE study is that the economic efficiency of the electricity markets need not decrease when a power system is operated under a stricter criterion as long as there is price-responsive demand. The proposed approach provides good insights into the ramification of changing the security criterion on both qualitative and quantitative basis.

We next illustrate the application of the proposed approach to the study of the ISO-NE system and markets under multi-settlement environment. The objectives of our studies are to quantify the economic efficiency of the ISO-NE multi-settlement markets as a function of the security criterion in force, to investigate the impacts of the of the financial entity participation on the ISO-NE system and markets and to quantify the impacts on the ISO-NE market performance of a security criterion change from the criterion in force to a modified $(n-1)$ security,

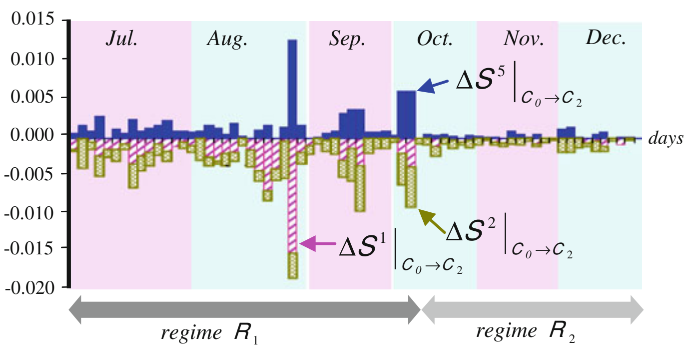


Fig. 13 Change in each area's contributions to auction surplus under $\mathbf{C}_2$

$\mathbf{C}_1$. We apply the proposed approach to quantitatively analyze the ISO-NE multi-settlement system performance. We assess the impacts of the participation of financial entities in the DAMs by performing a side-by-side comparison of the outcomes of the DAMs and the associated RTMs without and with such players. A particularly insightful aspect of the comparison is the set of values for the deviation metrics of the physical entities. In the following study, we quantify the impacts of a change in the security criterion from the current security criterion in force, $\mathbf{C}_0$, to $\mathbf{C}_1$ and compare the observed impacts under the two criteria.

We use the same 40 representative days from 2005 and 2006 to study the DAMs and their associated RTMs. For the discussion in this paper, we focus specifically on the four contiguous peak-demand hours of each selected day and analyze the values of metrics of interest for those 160 h. We start out with the evaluation of the ISO-NE multi-settlement system performance under the security criterion in force to determine the values of the metrics for the reference case for the study.

We perform market clearing for the DAMs and their associated RTMs for the selected 160 h and quantify the market performance metrics under the security criterion $\mathbf{C}_0$. We first focus on the DAM-RTM MW deviations. As the real-time demand in each RTM is considered to be fixed, the cleared demand values are not a function of the security criterion, per se, as long as the security-constrained market problem is feasible. We compare the fixed real-time demand in each of the M RTMs associated with the demand cleared in a DAM to evaluate the deviation metrics. We plot in Fig. 14 the demand values for the selected 160 h. We note that the real-time demand values exceed the DAM demand in the selected 160 h. As these hours are representative of the ISO-NE system past behavior, they correctly indicate that the RTM demands, typically, exceed the DAM demands. Therefore, there may be a need for additional physical generation in the real time over the amounts cleared in the DAMs.

We examine the physical demand and generation deviations and use the plots in Fig. 15 to gain insights into their nature. These plots indicate that both the physical

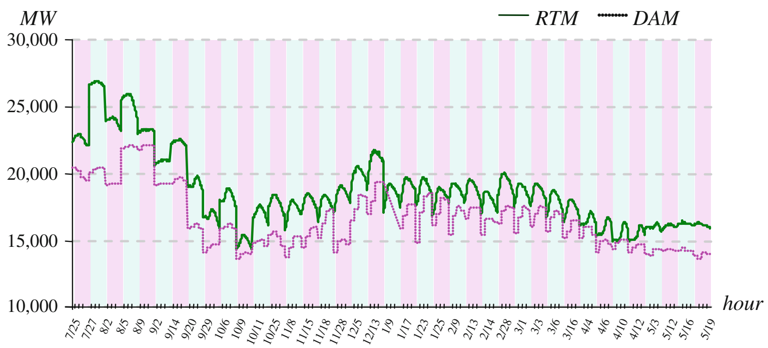


Fig. 14 Cleared demand in the DAMs and in their associated RTMs for the selected 160 hours in the study period

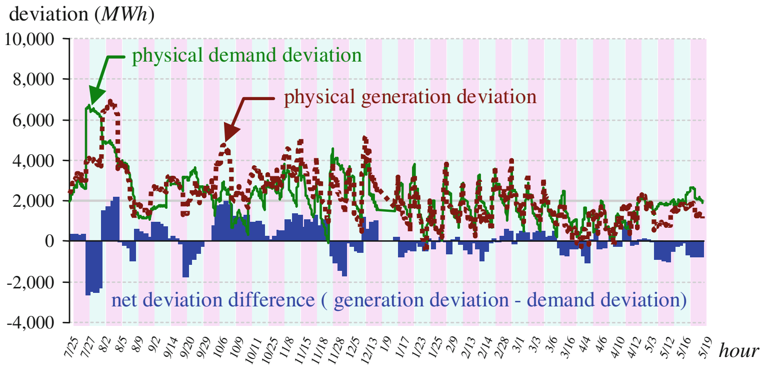


Fig. 15 The physical demand deviation, the physical generation deviation and the net deviation difference for the selected 160 hours in the study period

demand and the generation deviations are positive for the hours under consideration. Also, the positive values indicate that as much as 75% of the real-time demand and generation are cleared in the DAM. This result indicates that there is a need for additional generation in the real time. The plot of the net differences between the generation and the load deviations, Fig. 15, indicates the impacts of the net positions of the financial players in the DAMs. While there are daily variations in the financial entities' net positions, their range is up to 10% of the real-time demand, with the more pronounced impact in the higher demand days.

We now discuss the economic aspects of the secure operations of the power system. Analysis of the DAM-RTM price deviation metric indicates that, on average, the prices are higher in the DAMs than in their associated RTMs. Such results are clearly visible in the plots of the price deviation duration curves of the import areas $\mathcal{A}^1, \mathcal{A}^2$ and the export area $\mathcal{A}^5$. The area-wide price deviation measure of an area is evaluated using the load-weighted average of the prices in the area for a snapshot system. We observe that the price deviations are more pronounced for the import areas $\mathcal{A}^1$ and $\mathcal{A}^2$ than for the export area $\mathcal{A}^5$. For the study hours selected, the area $\mathcal{A}^2$ price deviations are larger than those of any other area indicating that congestion has more pronounced impacts on this area than other areas. The price deviation results also indicate that the physical sellers in the import areas capture more revenues for their real-time production in the 160 h of the study period.

Under these conditions, financial entities have more incentives to be sellers in the import area $\mathcal{A}^2$ than in any other area. If the financial sellers were to participate more intensely in the import area $\mathcal{A}^2$, then a decrease in the import area $\mathcal{A}^2$ DAM prices would result and, therefore, the price convergence would be improved. Given the nature of the physical generation and the demand deviations, we conjecture that financial entities may expect higher price deviations in the peak-demand periods and therefore they may adjust their bidding behaviors to clear more quantities in the DAMs in which they participate.

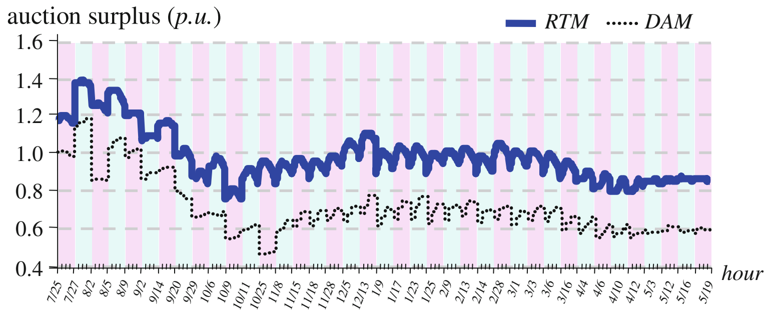


Fig. 16 The normalized auction surplus attained in the DAMs and the associated RTMs for the selected 160 hours in the study period

Next, we turn our attention to assessing the auction surplus of multi-settlement markets. We use the value of τ= 1,000 \$/MWh for the fixed demand. We choose this value on the basis of that it is the authorized bid/offer price cap in the ISO-NE markets and it is a reasonable proxy of the willingness to pay of the buyers with fixed demands. We evaluate using τ the auction surplus for the DAMs and the associated RTMs. We summarize the results in the plots given in Fig. 16 of the normalized auction surplus values for the 160 h in the study period. We normalize the auction surplus values using the average RTM auction surplus value so as to provide a meaningful comparison of the observed results. The positive load deviations and the fact that they represent fixed demands imply that the auction surplus outcomes are higher in the RTMs than in the DAMs. We next examine the individual components of the deviations of the auction surplus in the DAMs and their associated RTMs.

We investigate the deviations in the bid/offer surpluses of the physical market participants using their normalized values, with the base value being the RTM

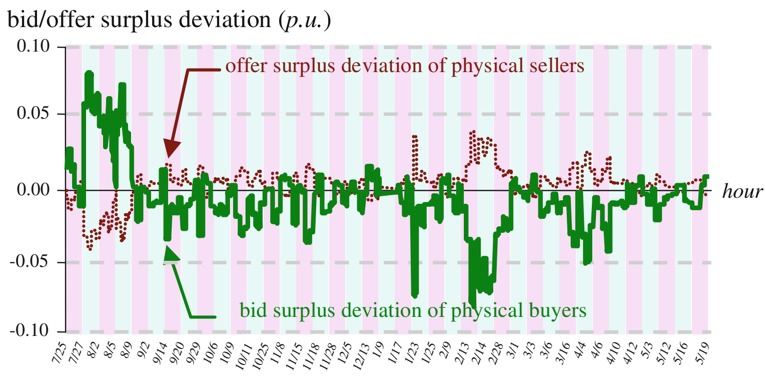


Fig. 17 Deviations in the offer (bid) surpluses of the physical sellers (buyers) for the selected 160 h in the study period

auction surplus. We provide the plots of the physical buyers and sellers in Fig. 17. We note that the physical sellers capture additional revenue for their real-time production for the majority of the hours in the simulation period. Therefore, the physical buyers pay a “premium” for that portion of their real-time demand needs that is cleared in the DAM. The plots clearly demonstrate that the sum of the bid/offer surplus deviations is not equal to zero, due to the financial entity participation, the bilateral transactions and the congestion rents. The metrics in Eqs. 18–35 serve to provide the quantification of the multi-settlement system performance for the 160 h of the study period under the reference criterion $\mathbf{C}_0$. We use these results as the reference basis for the comparative studies which we discuss next.

We examine the impacts that the financial players have on the market performance under the ISO-NE security criterion $\mathbf{C}_0$ in force. We first evaluate the impacts by considering the market operations without and with the participation of the financial entities in the DAMs. The difference between the two cases quantifies the contribution of the financial players in the multi-settlement environment. We evaluate the physical demand deviations, as well as the price deviations observed for the two cases.

Without financial entities in the DAM, lower physical demand is cleared in the DAM than in the case with the financial entity participation. Therefore, more generation is required in real time to compensate for the lower demand in order to ensure near-real-time system security. In fact, the ISO-NE study indicates that, on average, 700 MW additional output is required in real time without financial entity participation. Such an increase clearly indicates that the absence of financial entity participation makes the task to operate the near-real-time ISO-NE system securely more difficult. We find that financial entity participation leads to better forecasts of physical generation and consumption resulting in improved near-real-time system security. The plots of the cleared DAM demand without and with financial entity participation together with the real-time demand needs for the 160 h in the study period are given in Fig. 18.

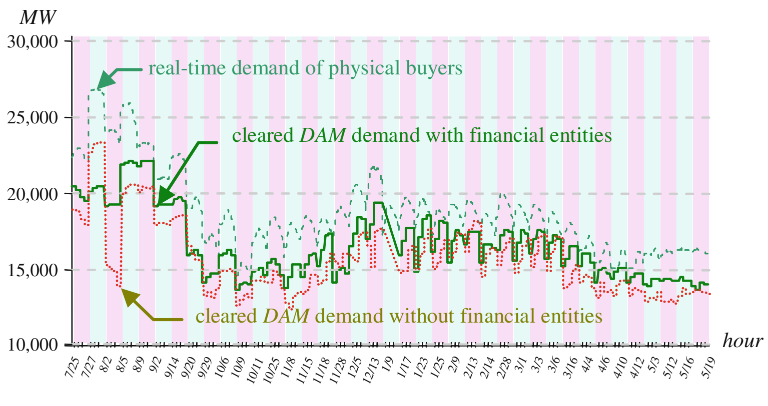


Fig. 18 Comparison of the cleared demands in the *DAM*s without and with financial entities for the selected 160 h in the study period

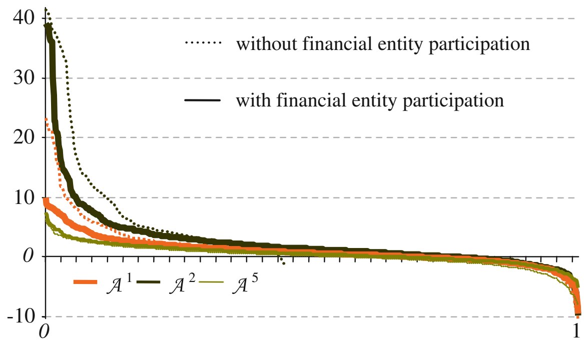


Fig. 19 Price deviation duration curves for the areas $\mathcal{A}^1, \mathcal{A}^2$ and $\mathcal{A}^5$ with and without financial entity participation

The most striking fact about financial entity participation can be discerned from examining the DAM-RTM price deviation results without and with financial entities. We superimpose in Fig. 19 the price deviation duration curves for the areas $\mathcal{A}^1, \mathcal{A}^2$ and $\mathcal{A}^5$ without the financial entity participation on those with their participation shown above in Fig. 20. The financial entity participation markedly reduces the deviation values for the areas $\mathcal{A}^1$ and $\mathcal{A}^2$. Since such a decrease corresponds to the desirable price convergence, its impact is very significant and attains the desired objective of price convergence that leads to improved market efficiency. Furthermore, our findings indicate that absent financial entity participation, the system is more congested in the DAMs, leading to the attainment of higher congestion rents than those obtained with the financial entity participation. In addition, system congestion impacts the prices of the import areas $\mathcal{A}^1$ and $\mathcal{A}^2$ more markedly than the case with financial entity participation. Therefore, financial entity participation reduces inter-area system congestion.

This side-by-side comparison results indicates very clearly the important role that financial entities play in electricity markets. Their participation decreases the magnitude of the physical demand deviations. In turn, these lower deviations make the management of near-real-time operations easier and, moreover,

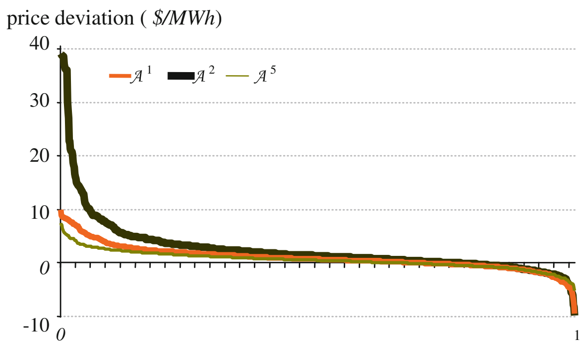


Fig. 20 Price deviation duration curves for the areas $\mathcal{A}^1, \mathcal{A}^2$ and $\mathcal{A}^5$ for the selected 160 h in the study period

improve near-real-time system security. In terms of market performance, the participation of financial entities decreases the magnitude of the price deviations.

We next study the impacts on the multi-settlement performance of a security criterion change from the reference criterion $\mathbf{C}_0$, to $\mathbf{C}_1$. For the security criterion $\mathbf{C}_1$, we perform market clearing of the DAMs and their associated RTMs for the selected hours in the study period and evaluate the market performance metrics. We compare the values of the metrics of interest with respect to those under the reference criterion $\mathbf{C}_0$.

The change from the security criterion $\mathbf{C}_0$ to $\mathbf{C}_1$ impacts the available transfer capability of the system, which, in turn, affects the ability of the import areas to bring in energy from the export area. Indeed, the examination of the ISO-NE results indicates increased import capabilities of the import areas for each hour of the given study period [35]. The increase in transfer capability has economic impacts, which we quantify from the changes in the auction surplus. We compute the hourly auction surplus values under the security criterion $\mathbf{C}_1$ for each selected hour of the study period and normalize them using the average value of the hourly auction surplus under the reference criterion $\mathbf{C}_0$. We note that the utilization of the increased import capabilities leads to increased auction surplus. We may view such an improvement as a measure of the "costs" of not violating the constraints associated with the double element contingencies in $\mathbf{J}_{\mathbf{C}_0}$. There are also a number of hours during which the change in security criterion from $\mathbf{C}_0$ to $\mathbf{C}_1$ has no impacts on the auction surplus. For such hours, the double element contingencies have zero economic impacts. We plot the changes in the normalized auction surplus values corresponding to the security criterion change in Fig. 21.

We next discuss the impacts of the change of security criterion from $\mathbf{C}_0$ to $\mathbf{C}_1$ on the market participants' bid/offer surpluses. The change of security criterion from $\mathbf{C}_0$ to $\mathbf{C}_1$ has widely varying impacts on the different market participants within the different areas. For illustration purposes, we consider five specific days to discuss the impacts. The security criterion change results in the greater utilization of the export area sellers and, therefore, in the decreased production of the

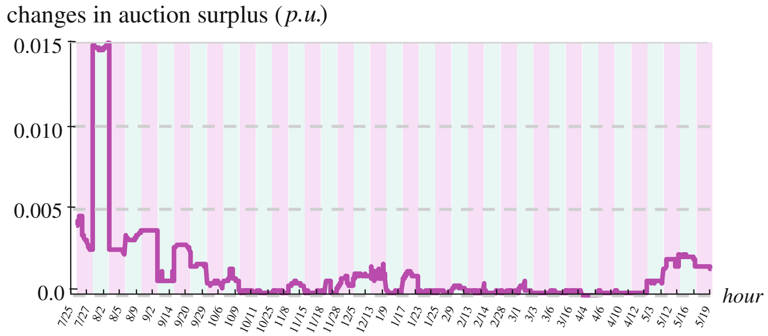


Fig. 21 Auction surplus change due to the criterion change from $\mathbf{C}_0$ to $\mathbf{C}_1$

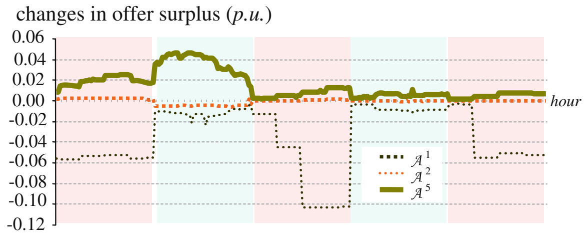


Fig. 22 Changes of the physical sellers' offer surpluses in response to the security criterion change from $\mathbf{C}_0$ to $\mathbf{C}_1$

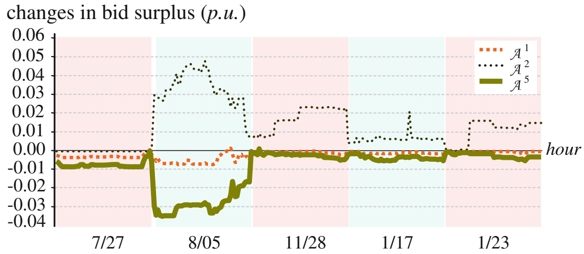


Fig. 23 Changes of the physical buyers' bid surpluses in response to the security criterion change from $\mathbf{C}_0$ to $\mathbf{C}_1$

import area physical sellers. Such a change leads to a corresponding change in the surpluses of the players in the various areas. In Fig. 22, we plot changes in the physical sellers' offer surpluses in areas $\mathcal{A}^1$, $\mathcal{A}^2$, and $\mathcal{A}^5$for the five selected days.

The impacts have almost the opposite effects on the surpluses of the physical buyers: while the bid surpluses of the export area physical buyers are decreasing, those in the import areas are increasing. The physical buyers within the import areas are able to meet their demand using more economic resources from the export area $\mathcal{A}^5$ to take advantage of the increased transfer capabilities, thereby decreasing their payments. In fact, the changes in the bid surpluses are particularly more pronounced for the import area $\mathcal{A}^2$ physical buyers than other areas' physical buyers as shown in Fig. 23.

The impacts of changing the security criterion on the surpluses of the financial entities are minor and of little significance compared to those impacts on the players with physical assets for a change in the security criterion. Overall, the relatively small dollar impacts due to the change of the security criterion from $\mathbf{C}_0$ to $\mathbf{C}_1$, as evident from the Figs. 21, 22, 23, furthermore justify that the current security criterion in force, $\mathbf{C}_0$, is appropriate for the ISO-NE markets [36].

Through the ISO-NE study, we gain important insights into the system security and its economics in a multi-settlement environment. The proposed approach effectively captures the impacts of the DAM clearing on the market participant bid/offer surpluses. Furthermore, the price signals, provided by the multi-settlement system, encourage financial entity participation which, in turn, leads to not only improvements in the overall market performance but also in the ability of the RTO to ensure near-real-time system security.

6 Concluding Remarks

The maintenance of secure system operations is a highly challenging task that became even more complex with the prominence of electricity markets. We use the insights we gained into the tight coupling between market and system operations under restructuring to characterize analytically the inter-relationships between the secure power system operations and the performance of the electricity markets. Such a characterization allows the development of an integrated analysis approach to quantify the economics of secure power system operations. This approach permits the quantification of the market performance as a function of security criterion and provides, for the first time, the means to provide an economic justification for a modification the security criterion. Furthermore, the approach is useful for the costs/benefits analysis of network improvements to mitigate the market performance impacts of a set of contingencies and their associated security control actions. An important application is to the assessment of the impacts of specific behavioral changes in market participants on system security. The generalization of the approach is made by its extension to quantitatively characterize the linkages between the real-time system operations and the day-ahead markets (DAMs) and their associated real-time markets (RTMs) for use in a multi-settlement environment. The extended approach provides the ability to explicitly show that the auction surplus attained in the multi-settlement system is equivalent to sum of the auction surplus attained in each RTM. Therefore, the mere presence of the DAMs results in surplus transfers among market participants. Furthermore, the extended approach provides a very useful tool to analyze the nature of the DAM-RTM price deviations and the impacts of financial entities on near-real-time system security.

We illustrate the application of the proposed approaches on the large-scale ISO-NE system in a number of studies. The results provide useful insights into the multi-faceted nature of issues that arise in the current tightly coupled market and system operations. In fact, the studies on the economics of the system security provide important insights into the role of price-responsive demand and that of specific selected security control actions measured by the economic efficiency of the electricity markets. A key result is that this efficiency need not decrease when a power system is operated under a stricter criterion, as long as there is effective price-responsive demand and appropriate utilization of the corrective control capabilities of the resources. Furthermore, the ISO-NE application study in the multi-settlement environment indicates that financial entity participation not only results in reduced DAM-RTM price deviations but also leads to DAM dispatch results that are “closer” to those of their associated RTMs. Therefore, financial player participation improves the ability of the system operator to ensure real-time system security.

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