An Analytical Framework for Short-Term Resource Adequacy in Competitive Electricity Markets

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***Abstract*— Short-term resource adequacy, a key component of system reliability, is the ability of a system with a fixed resource mix to meet the load at all times. In the competitive environment, the interaction of markets and reliability has raised this issue to new prominence. Market design influences significantly the behavior of market players, which, in turn, impacts the capacity adequacy of the system. The extent of such impacts is well illustrated by the California market experience during the 2000–2001 crisis. Current resource adequacy tools fail to explicitly consider the interactions between market design, the behavior of market players and system reliability. We construct an analytical framework for short-term resource adequacy that explicitly considers the interactions between markets and reliability. The framework models both the physical world by representing the resources and the load demand, and the market world, by including the market design, the market players' behavior and their interactions with the physical world. We use the framework to assess the impacts of market player behavior on various test systems. Representative results are provided.**

***Index Terms*— reliability, resource adequacy, electricity markets, strategic behavior, capacity gaming.**

I. Introduction

The electric system is said to be reliable when consumers receive all the electricity they demand with the desired quality. The study of electric system reliability consists of the investigation of system security and system adequacy. Security is the ability of the system to withstand sudden disturbances. Adequacy is the ability of the system to meet the aggregate customer demand [1]. Resource adequacy addresses the need to have "sufficient" resources in place to meet the forecasted demand taking into account the uncertainty of the environment and the salient characteristics of electricity, including the lack of large-scale storage and the limited demand responsiveness of load to price. Under the conventional vertically integrated structure, the reliability decisions were the responsibility of the utility that owned and operated the resources and the transmission network. In the market environment, an independent entity, which we refer to by the generic term independent grid operator, or IGO, is responsible for system reliability. Our focus is on the resource adequacy of the system over a short period of the order of months. For such periods, the resource mix remains fixed and the only decision variables for ensuring resource adequacy are the offered capacities of the existing supply sources and demand bids of price responsive buyers in electricity markets.

Under restructuring, resource adequacy assurance has become very complex, as seen in the 2000–2001 California electricity crisis. The underlying commodity in all electricity markets, be they energy or ancillary services markets, is capacity. Since sellers need not offer all their capacity to serve the demand, they may engage in so-called *physical capacity withholding* or *capacity gaming* [2]. Any withholding action impairs the reliability, and consequently the short-term resource adequacy depends on market player behavior. In fact, absent the formulation of specific rules, withholding may result in capacity deficiency, which has become a concern in various jurisdictions. FERC's attempts to guide market design [3] recognize the importance of the resource adequacy issue to well functioning markets.

Current resource adequacy tools fail to explicitly consider the interactions between market design, the behavior of market players and system reliability. To overcome this deficiency, we construct an analytical framework for short-term resource adequacy that explicitly considers the interactions between markets and reliability. The framework models both the physical world by representing the contribution of the resources and the load demand to reliability, and the market world, by including the market design, the market players' behavior and their interactions with the physical world. In this way, we can develop explicit relationships between economics and resource adequacy. We illustrate the capabilities of the framework by using it to assess the impacts of market player behavior on reliability on various test systems.

The paper contains three more sections. In the next section, we construct the analytic framework. In section 3, we present the applications of the framework and show illustrative simulation study results. We make concluding remarks and state the scope of further work in the last section.

II. Analytic Framework

We consider an isolated system operated by an IGO and assume that its transmission network has ample transfer capability. As such, we assume that there is no congestion and ignore all other network considerations. The conventional approach to adequacy evaluation is based on the physical characteristics of the resources and does not consider market outcomes. To consider the impacts of physical capacity withholding on reliability, we need models of the day-ahead market and seller behavior.

We define one hour as the smallest indecomposable unit of time. The time horizon of interest is H hours. In our

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discussion of the day-ahead market and seller behavior models, we focus on a snapshot of the system in hour *h*. For each hour *h* of the day-ahead market, we model the total system demand as the sum of the forecast ℓ_h and a random variable (r.v.) $\Delta \underset{\sim}{L}_h$. For simplicity, we assume that

$$\Delta \underset{\sim}{L}_h = \begin{cases} 0 & \text{with probability } p_h \\ \Delta\ell_h > 0 & \text{with probability } \left(1-p_h\right). \end{cases} \tag{1}$$

There are S generation firms denoted by $s^1, s^2, ..., s^S$. We assume the available capacity α^i_{jh} of generator *j* of seller s^i in hour *h* is a known deterministic variable in the day-ahead of the hour *h*. We denote the available capacity of seller s^i in hour *h* by $\alpha^i_h = \sum_j \alpha^i_{jh}$.

We consider a pool market paradigm, where we assume the energy and reserves markets are combined into the single *energy and reserves market* (ERM) [4]. Each seller's offer in the ERM must be backed by deliverable capacity and energy, and each buyer's bid is accompanied by the obligation to take delivery of the purchases.

We further assume the demand of each buyer is fixed and independent of the ERM prices, and so the total demand is fixed and independent of the ERM prices. The total market demand for energy is ℓ_h *MWh*, and the total market demand for reserves is β_h *MW*. The specification of β_h takes explicitly into account the impacts of $\Delta\ell_h$. Sellers submit offers for their generators and we model the capacity of each generator by a set of blocks whose sum of capacities equals the generator capacity. The k^{th} *block offer* from generator *j* of seller s^i with capacity κ^{ik}_{jh} is defined by the energy and reserves *offer prices* $\sigma^{ik}_{jh} \in \left[0, \bar{\rho}_e\right]$ and $\varsigma^{ik}_{jh} \in \left[0, \bar{\rho}_r\right]$, respectively, and the reserves *capacity* $\mu^{ik}_{jh} \leq \kappa^{ik}_{jh}$. The offer caps $\bar{\rho}_e$ and $\bar{\rho}_r$ for energy and reserves, respectively, prevent sellers from offering at prices above the caps so as to limit *economic withholding* [5, p. 454]. This is a simple model of the mitigation practices used in actual markets [6]. We define the vectors $\underline{\boldsymbol{\sigma}}_h$, $\underline{\boldsymbol{\varsigma}}_h$, $\underline{\boldsymbol{\kappa}}_h$ and $\underline{\boldsymbol{\mu}}_h$ consisting of the block offer prices and capacities of all the sellers. We denote the energy and reserves provided by the block with capacity κ^{ik}_{jh} by e^{ik}_{jh} and r^{ik}_{jh}, respectively. We construct the vectors $\underline{\boldsymbol{e}}_h$ and $\underline{\boldsymbol{r}}_h$, consisting of the energy and reserves provided by all the block offers. For notational simplicity, in the remainder of our discussion we drop the index *h*.

The IGO determines the hour-*h* ERM outcomes by maximizing the *social welfare* [7]. Under the assumption of a price-independent demand, the maximization of the social welfare is equivalent to the minimization of the cost function $\mathscr{C}(\cdot,\cdot)$ in the ERM to meet the energy and reserves needs

$$\mathscr{C}\left(\underline{\boldsymbol{e}}, \underline{\boldsymbol{r}}\right) \triangleq \underline{\boldsymbol{\sigma}}'\underline{\boldsymbol{e}} + \underline{\boldsymbol{\varsigma}}'\underline{\boldsymbol{r}}. \tag{2}$$

The determination of the optimal $\underline{\boldsymbol{e}}^*$ and $\underline{\boldsymbol{r}}^*$ variables entails the solution of the linear programming problem

$$\left.\begin{array}{l} \underset{\underline{\boldsymbol{e}}, \underline{\boldsymbol{r}}}{min} \ \mathscr{C}\left(\underline{\boldsymbol{e}}, \underline{\boldsymbol{r}}\right) \\ s.t. \\ \qquad \underline{\mathbf{1}}'\underline{\boldsymbol{e}} = \ell \quad \leftrightarrow \quad \rho_e \\ \qquad \underline{\mathbf{1}}'\underline{\boldsymbol{r}} = \beta \quad \leftrightarrow \quad \rho_r \\ \qquad \underline{\boldsymbol{e}} + \underline{\boldsymbol{r}} \leq \underline{\boldsymbol{\kappa}} \\ \qquad \underline{\boldsymbol{r}} \leq \underline{\boldsymbol{\mu}} \\ \qquad \underline{\boldsymbol{e}}, \underline{\boldsymbol{r}} \geq \underline{\boldsymbol{0}} \end{array}\right\} \left(ERMP\right). \tag{3}$$

A feasible solution of (3) is characterized by the energy and reserves prices ρ^*_e and ρ^*_r, respectively, being equal to the asking prices of the most expensive blocks producing energy and reserves, respectively. Providers of reserves receive the energy price in addition to the reserves price whenever they are asked to produce energy by the reserves serving blocks. Since there are two commodities sold in the ERM, a block that is offered to sell energy and reserves with offer prices below the market clearing price will sell the commodity that provides the largest savings to the IGO [8]. We denote the total capacity offered by seller s^i by κ^i_T, and the total capacity offered by all sellers by

$$\kappa_T = \sum_{i=1}^{S} \kappa^i_T. \tag{4}$$

In cases where there is shortage, e.g., $\kappa_T < \ell$, (3) is infeasible, and ERM prices are limited by the administratively set ERM price caps $\bar{\bar{\rho}}_e$ and $\bar{\bar{\rho}}_r$ for energy and reserves, respectively. The caps satisfy $\bar{\bar{\rho}}_e > \bar{\rho}_e$ and $\bar{\bar{\rho}}_r > \bar{\rho}_r$ to allow the representation of scarcity rents [5, p. 70]. In light of the physical deliverability requirement on each seller's offers, the ERM constitutes in effect a *physical* market.

We next discuss the modeling of the market sellers' behavior. We assume each seller's objective is to maximize its expected profits by selecting the offer variables. We further assume that the sellers opt to offer all their available capacity rather than withholding capacity whenever both conducts result in the same expected profits. We distinguish between the two types of sellers, the *price takers* and the *price setters* [9, p. 46], also known as *strategic sellers* [4]. Price takers cannot affect the market price, but strategic sellers do affect the market price. A price taker optimizes its offering strategy by offering all its available capacity at marginal costs [4], [10].

For simplicity, we assume that there is only one strategic seller $s^{\hat{i}}$. By doing so, we capture the impacts of the strategic behavior on reliability while avoiding the need of an equilibrium model, e.g., Nash equilibrium, and the complications they bring, e.g., existence of multiple equilibria. We assume that the strategic seller has perfect information on its competitors' offers for the hour *h* ERM. The decision of seller $s^{\hat{i}}$ is on the amounts $e^{\hat{i}}$ of energy and $r^{\hat{i}}$ of reserves to sell in the ERM, with

$$e^{\hat{i}} = \sum_j \sum_k e^{\hat{i}k}_j \quad \text{and} \quad r^{\hat{i}} = \sum_j \sum_k r^{\hat{i}k}_j. \tag{5}$$

The seller $s^{\hat{i}}$ impacts the market prices, which we write as explicit functions of $e^{\hat{i}}$ and $r^{\hat{i}}$:

$$\rho_e^* = \rho_e^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right) \text{ and } \rho_r^* = \rho_r^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right). \tag{6}$$

These functions are effectively the *residual demand* functions for the strategic seller, and can be constructed in view of the perfect information assumption. Due to the nature of the offers, $\rho_e^{\hat{i}}(\cdot,\cdot)$ and $\rho_r^{\hat{i}}(\cdot,\cdot)$ are piecewise constant functions of $e^{\hat{i}}$ and $r^{\hat{i}}$. The two-tuple $(e^{\hat{i}}, r^{\hat{i}})$ is *attainable* if and only if there exists an offer that lets seller $s^{\hat{i}}$ sell $e^{\hat{i}}$ *MWh* and $r^{\hat{i}}$ *MW*. We next characterize the attainable set $\mathbb{F}^{\hat{i}}$:

- seller $s^{\hat{i}}$ sells nonnegative quantities,
- the sales cannot exceed the available capacity $\alpha^{\hat{i}}$, and
- whenever $r^{\hat{i}}$ is positive, buying reserves from seller $s^{\hat{i}}$ at the lowest possible offer price ($0/*MW*) has to provide more savings to the IGO than buying energy from seller $s^{\hat{i}}$ at the highest possible offer price ($\$\,\bar{\rho}_e$/*MWh*).

In view of this, we can show that the attainable set $\mathbb{F}^{\hat{i}}$ is given by

$$\mathbb{F}^{\hat{i}} = \left\{ \begin{array}{l} \left(e^{\hat{i}}, r^{\hat{i}}\right) \geq 0 : e^{\hat{i}} + r^{\hat{i}} \leq \alpha^{\hat{i}}, \\ r^{\hat{i}}\left[\rho_e^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right) - \bar{\rho}_e\right] \leq r^{\hat{i}} \rho_r^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right) \end{array} \right\}. \tag{7}$$

Seller $s^{\hat{i}}$ selects the attainable two-tuple $(e^{\hat{i}**}, r^{\hat{i}**})$ that maximizes its expected profits. With $\beta = \Delta\ell$ and neglecting the costs of reserves, the expected profits of seller $s^{\hat{i}}$ are

$$\begin{aligned} \Pi^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right) = {} & p\left[\rho_e^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right) e^{\hat{i}} - \chi_e^{\hat{i}}\left(e^{\hat{i}}\right) + \rho_r^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right) r^{\hat{i}}\right] \\ & + (1-p)\left[\rho_e^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right)\left(e^{\hat{i}} + r^{\hat{i}}\right)\right. \\ & \left. - \chi_e^{\hat{i}}\left(e^{\hat{i}} + r^{\hat{i}}\right) + \rho_r^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right) r^{\hat{i}}\right], \end{aligned} \tag{8}$$

where $\chi_e^{\hat{i}}(\cdot)$ is the energy production costs function. The strategic seller determines $e^{\hat{i}**}$ and $r^{\hat{i}**}$ as the solution of

$$\max_{e^{\hat{i}}, r^{\hat{i}}} \left\{\Pi^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right), \left(e^{\hat{i}}, r^{\hat{i}}\right) \in \mathbb{F}^{\hat{i}}\right\} \quad (SSP).^1 \tag{9}$$

The decision variables in (9) are sale quantities, not offer parameters. Once $(e^{\hat{i}**}, r^{\hat{i}**})$ is known, seller $s^{\hat{i}}$ constructs an offer to attain its objective of selling $e^{\hat{i}**}$ *MWh* and $r^{\hat{i}**}$ *MW* in the ERM [8, p. 93]. Due to the perfect information assumption, the relationships between the solutions of the (*SSP*) and the (*ERMP*) are

$$e^{\hat{i}*} = e^{\hat{i}**} \text{ and } r^{\hat{i}*} = r^{\hat{i}**}. \tag{10}$$

Whenever there is shortage,

$$\bar{\bar{\rho}}_e = \rho_e^{\hat{i}}(e^{\hat{i}**}, r^{\hat{i}**}) > \bar{\rho}_e \text{ and/or } \bar{\bar{\rho}}_r = \rho_r^{\hat{i}}(e^{\hat{i}**}, r^{\hat{i}**}) > \bar{\rho}_r, \tag{11}$$

and so any offer price is below the market price. Thus, if seller $s^{\hat{i}}$ were to offer $\kappa_T^{\hat{i}} > e^{\hat{i}**} + r^{\hat{i}**}$, seller $s^{\hat{i}}$ would sell more energy and/or reserves than the optimal two-tuple $(e^{\hat{i}**}, r^{\hat{i}**})$. Hence, whenever (11) holds the strategic seller offers exactly $e^{\hat{i}**} + r^{\hat{i}**}$. Therefore,

$$\kappa_T = \begin{cases} \sum_i \alpha^i & \text{if (11) does not hold} \\ \sum_{i: i \neq \hat{i}} \alpha^i + e^{\hat{i}**} + r^{\hat{i}**} & \text{otherwise,} \end{cases} \tag{12}$$

Thus, the conditions under which seller $s^{\hat{i}}$ exercises physical withholding are (11) and

$$e^{\hat{i}**} + r^{\hat{i}**} < \alpha^{\hat{i}}. \tag{13}$$

Clearly, without mitigation, i.e., $\bar{\bar{\rho}}_e = \bar{\rho}_e$ and $\bar{\bar{\rho}}_r = \bar{\rho}_r$, (11) would never hold and so there would be no physical withholding.

In light of the perfect information of the strategic seller assumption, the solution of the (*ERMP*) determines that of the (*SSP*). Thus, for all practical purposes they are solved simultaneously. Without perfect information, the (*ERMP*) would be solved first and, once the strategic seller offer is chosen, the (*SSP*) would be solved.

We conceptually arrange the models for the hour-*h* into two layers, as shown in Figure 1. The models of the load and the generation resources are grouped in the hour-*h* physical layer and the models of the *ERM* and the sellers are grouped in the hour-*h* market layer. The physical layer provides the load distribution and the available capacities. That information is used in the market layer to obtain the offered capacities from the (*SSP*). If the strategic seller is required to declare and offer all its available capacity, it may have strong incentives to declare the solution of the (*SSP*) as its available capacity. This is shown by the information flow going from the market layer to the physical layer.

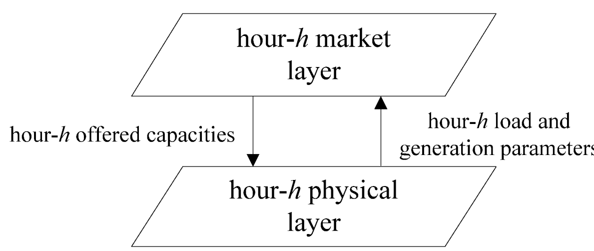

Fig. 1. Conceptual arrangement of the models for the hour *h*.

We next discuss the modeling of the physical load and generation resources during the *H*-hour period for the purposes of reliability evaluation. These are simulation models, there is no optimization involved in them. We represent the system's total demand in the *H*-hour period by the r.v. $\underset{\sim}{L}$. If the system is in hour *h*, then $\underset{\sim}{L} = \underset{\sim}{L}_h$. Using conditional probability,

$$\boldsymbol{P}\left\{\underset{\sim}{L} = \underset{\sim}{L}_h \,\middle|\, \text{hour } h\right\} = 1. \tag{14}$$

The distribution of $\underset{\sim}{L}$ is obtained from those of the hourly loads $\underset{\sim}{L}_h$ in a similar manner as the load duration curve is constructed from the chronological load curve. The *peak load* ℓ^p is defined as the maximum value $\underset{\sim}{L}$ may attain during the *H*-hour period,

[1] The (*SSP*) is a nonlinear optimization problem with a discontinuous objective function and a cumbersome feasible set due to the multiple products sold (energy and reserves). Its efficient solution has not been studied yet, and so we use an exhaustive search for the solution of the (*SSP*).

$$\ell^{p} = \max_{1 \le h \le H} \left\{ \ell_h + \Delta\ell_h \right\}. \tag{15}$$

We use the 2-state conventional model for the available generation in the H-hour period. The basic underlying assumption is that the units have uniform characteristics throughout the period. The *available capacity* of generator j owned by seller s^i is modeled by the r.v. $\underset{\sim}{A}{}_j^i$,

$$\underset{\sim}{A}{}_j^i = \begin{cases} g_j^i & \text{with probability } a_j^i \\ 0 & \text{with probability } \left(1 - a_j^i\right). \end{cases} \tag{16}$$

where g_j^i is the capacity and a_j^i is the *availability* of the unit j of seller s^i. The r.v.s $\underset{\sim}{A}{}_j^i$s and $\underset{\sim}{L}$ are assumed to be independent. The total available capacity of seller s^i is denoted by the r.v. $\underset{\sim}{A}{}^i = \sum_j \underset{\sim}{A}{}_j^i$. The capacity α_h^i is the realization of $\underset{\sim}{A}{}^i$ for the hour h. The system available capacity is denoted by the r.v. $\underset{\sim}{A} = \sum_i \underset{\sim}{A}{}^i$. The available reserves margin relative to the load is given by the r.v. $\underset{\sim}{R}$,

$$\underset{\sim}{R} = \frac{\underset{\sim}{A} - \underset{\sim}{L}}{\underset{\sim}{L}}. \tag{17}$$

We assess the system reliability in the H-hour period with the usual metrics used in reliability analysis [11]:

(i) the *loss of load probability*

$$\boldsymbol{P}\left\{ \underset{\sim}{L} > \underset{\sim}{A} \right\},$$

(ii) the *expected unserved energy*

$$H \cdot \boldsymbol{E}\left\{ \underset{\sim}{L} - \underset{\sim}{A} \,\middle|\, \underset{\sim}{L} > \underset{\sim}{A} \right\} \cdot \boldsymbol{P}\left\{ \underset{\sim}{L} > \underset{\sim}{A} \right\}, \text{ and}$$

(iii) the *expected outage costs*,

$$w \cdot H \cdot \boldsymbol{E}\left\{ \underset{\sim}{L} - \underset{\sim}{A} \,\middle|\, \underset{\sim}{L} > \underset{\sim}{A} \right\} \cdot \boldsymbol{P}\left\{ \underset{\sim}{L} > \underset{\sim}{A} \right\},$$

where w is the *value of lost load* [12] used in the assessment of the economic impacts. We explicitly distinguish the metric functions from their values by using the notation $LOLP$, $\mathscr{U}$, and $\mathscr{C}_o$, respectively, for their values.

Next, we incorporate the impacts of the market on reliability. The uncertainty in the available capacity for the month-ahead period results in uncertainty in the sellers' offers, and therefore in the capacity offered in the ERM and the ERM costs. To represent this uncertainty, we examine the distributions of the uncertain total capacity $\underset{\sim}{K}$ offered in the ERM, and the uncertain ERM costs $\underset{\sim}{D}$. If the system is in hour h and the available capacities are known, then $\underset{\sim}{D} = d_h$ and $\underset{\sim}{K} = \kappa_{Th}$, where $d_h = \mathscr{C}_h\left(\underline{\boldsymbol{e}}_h^*, \underline{\boldsymbol{r}}_h^*\right)$ and κ_{Th} are obtained from (3) and (12), respectively. Using conditional probability,

$$\boldsymbol{P}\left\{ \underset{\sim}{K} = \kappa_{Th} \,\middle|\, \{\text{hour } h\} \cap \left\{ \underset{\sim}{A}{}_j^i = \alpha_{jh}^i \; \forall\, i, j \right\} \right\} = 1 \tag{18}$$

and

$$\boldsymbol{P}\left\{ \underset{\sim}{D} = d_h \,\middle|\, \{\text{hour } h\} \cap \left\{ \underset{\sim}{A}{}_j^i = \alpha_{jh}^i \; \forall\, i, j \right\} \right\} = 1. \tag{19}$$

The distributions of $\underset{\sim}{K}$ and $\underset{\sim}{D}$, characterized by (1), (16), (18), and (19), can be obtained using Monte Carlo simulation [13], [14] or sampling all possible cases (if the number of generators and load values is small). In any case, as implied by (18) and (19), one starts by sampling the available capacity for each generator and the hour, which gives the load distribution (1). These data are used to compute κ_{Th} and d_h. The process is repeated until the number of desired samples is reached. The possibility of physical withholding exercise implies that $\underset{\sim}{K}$ need not be equal to $\underset{\sim}{A}$, and by the physical nature of the ERM,

$$\boldsymbol{P}\left\{ \underset{\sim}{K} \le \underset{\sim}{A} \right\} = 1. \tag{20}$$

In a competitive market setting, reliability depends on the sellers' behavior in the market. We explicitly incorporate market effects by replacing $\underset{\sim}{A}$ by the total offered capacity $\underset{\sim}{K}$ in *(i) – (iii)*, and denote with the superscript M the values taken by these metrics as a result of the ERM outcomes:

$$LOLP^M = \boldsymbol{P}\left\{ \underset{\sim}{L} > \underset{\sim}{K} \right\}, \tag{21}$$

$$\mathscr{U}^M = H \cdot \boldsymbol{E}\left\{ \underset{\sim}{L} - \underset{\sim}{K} \,\middle|\, \underset{\sim}{L} > \underset{\sim}{K} \right\} \cdot \boldsymbol{P}\left\{ \underset{\sim}{L} > \underset{\sim}{K} \right\}, \tag{22}$$

$$\mathscr{C}_o^M = w \cdot H \cdot \boldsymbol{E}\left\{ \underset{\sim}{L} - \underset{\sim}{K} \,\middle|\, \underset{\sim}{L} > \underset{\sim}{K} \right\} \cdot \boldsymbol{P}\left\{ \underset{\sim}{L} > \underset{\sim}{K} \right\}. \tag{23}$$

Given (20), it follows that $LOLP$, $\mathscr{U}$, and $\mathscr{C}_o$ overstate the system reliability, i.e., they are lower bounds for $LOLP^M$, $\mathscr{U}^M$, and $\mathscr{C}_o^M$, respectively. The market reserves margin is given by the r.v. $\underset{\sim}{R}{}^M$,

$$\underset{\sim}{R}{}^M = \frac{\underset{\sim}{K} - \underset{\sim}{L}}{\underset{\sim}{L}}. \tag{24}$$

The *service costs* $\mathscr{C}_s$ are defined as,

$$\mathscr{C}_s \triangleq H \cdot \boldsymbol{E}\left\{ \underset{\sim}{D} \right\}. \tag{25}$$

The service costs provide a measure of the sellers' revenues and the LSEs' payments in the H-hour period.

The conceptual basis of the framework consists of two interconnected layers, shown in Figure 2. We arrange each hour-h layer in the corresponding H-hour period layer, and conceptually connect the layers in a similar manner as the hourly layers are connected. The models in the framework comprehensively represent all the important factors to allow the analysis and simulation of general issues related to short-term resource adequacy.

III. Framework Applications

The framework provides the capability to quantify the impacts of market players' behavior on system reliability, and so it can also be applied in the analysis and simulation of the

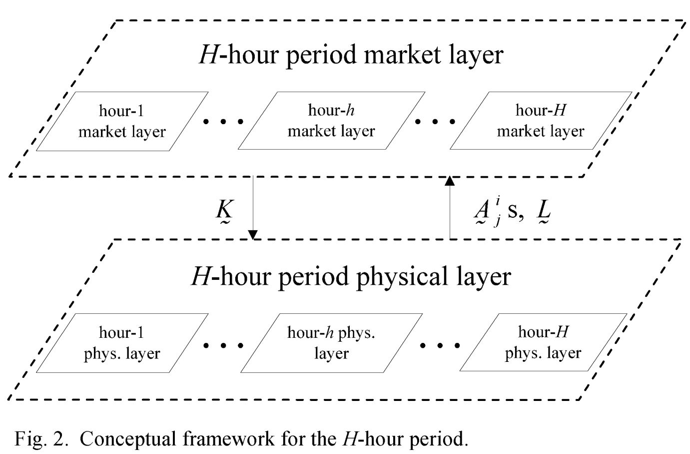

Fig. 2. Conceptual framework for the H-hour period.

TABLE I
TEST SYSTEMS DATA

test system	A	B
number of generation firms	8	87
total number of generators	10	100
peak demand (*MW*)	1650	17800
market cap for energy (*$/MWh*)	150	150
market cap for reserves (*$/MWh*)	30	30
offer cap for energy (*$/MWh*)	95	120
capacity margin (*%*)	42.4	19.1
strategic seller capacity (*MW*)	750	2500
strategic seller's generators	3	14
strategic seller's market share (*%*)	32	11.8

TABLE II
METRICS VALUES

test system	A		B	
r.v. used	$\underset{\sim}{K}$	$\underset{\sim}{A}$	$\underset{\sim}{K}$	$\underset{\sim}{A}$
loss of load probability	$1.46\ 10^{-2}$	$0.34\ 10^{-2}$	$8.80\ 10^{-4}$ ±0.02%	$0.61\ 10^{-4}$ ±0.01%
expected unserved energy (*MWh*)	$1.60\ 10^{3}$	$0.31\ 10^{3}$	$1.31\ 10^{2}$ ±0.02%	$0.14\ 10^{2}$ ±0.02%

impacts of market design on reliability. The framework presented has been applied to the design, analysis and simulation of short-term resource adequacy programs [8].

In the remainder of this section, we illustrate the capabilities of the framework by using it to assess the impacts of market player behavior on two test systems. Complete data for the test systems is found in [8], and we provide a summary in Table I. The values of the metrics, presented in Table II, are obtained by conditioning on the system state. In system A, all states were considered and so the results obtained are exact. For system B, since the number of states is very large, Monte Carlo simulation was used and so the results have an error, indicated in the table. All values of the metrics ignoring market outcomes are strictly smaller than those considering market outcomes, showing that the exercise of physical withholding hurts reliability in the test systems.

We show an example of an hour where the strategic seller physically withholds capacity in test system A. In this hour, the demand can take the values of 1000 and 1150 *MWh*, the strategic seller has 350 *MW* of available capacity, and the price takers have a total of 800 *MW*. In this example, it turns out that not selling reserves is optimal for the strategic seller, i.e., $r^{\hat{i}**} = 0$. The energy price as a function $\rho_e^{\hat{i}}\left(\cdot, r^{\hat{i}**}\right)$ of the energy sold by the strategic seller is plotted in Figure 3. If the strategic seller sells less than 200 *MWh*, the energy price is equal to the price cap, 150 $/*MWh*. Otherwise, the price is equal to the offer price of the strategic seller, and since the highest offer price is 95 $/*MWh*, the energy price is equal to 95 $/*MWh* in this case. The price reduction from $e^{\hat{i}} = 200$ to $e^{\hat{i}} = 201$ *MWh* translates into a profit reduction, as shown in Fig. 4, and so the solution of (*SSP*) gives $e^{\hat{i}**} = 200$ *MWh*. In this case, $\rho_e^{\hat{i}}(e^{\hat{i}**}, r^{\hat{i}**}) = \bar{\bar{\rho}}_e$ and $\rho_r^{\hat{i}}(e^{\hat{i}**}, r^{\hat{i}**}) = \bar{\bar{\rho}}_r$, and so,

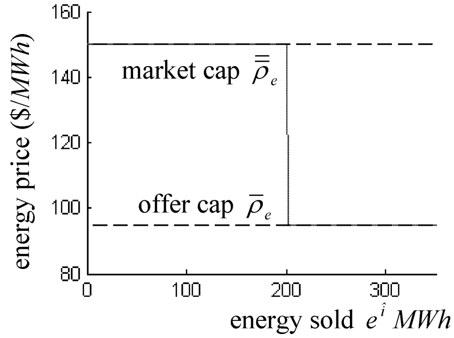

Fig. 3. Price of energy as a function of the energy sold by the strategic seller for a given system state, if the strategic seller does not sell reserves.

by (12), the strategic seller will withhold capacity. To see why, suppose that the strategic seller does not withhold, i.e., it offers 350 *MWh* in the market, none of which is offered to provide reserves. Then, the total capacity offered is equal to the maximum value the demand can take. Thus, all capacity offered sells either energy or reserves. The strategic seller sells 350 *MWh* of energy, and so its profits are smaller than in the case with physical withholding. The price takers sell 650 *MWh* of energy and 150 *MW* of reserves. The case where the strategic seller offers reserves is even more disadvantageous. Due to physical withholding, the loss of load probability for the hour is equal to $(1-p_h)$, even though there is enough available capacity to supply all the demand. The possible values for the available reserve margin in the hour are 0.15 and 0, while the possible values for the market reserves margin are 0 and -0.13. In this example, the strategic seller

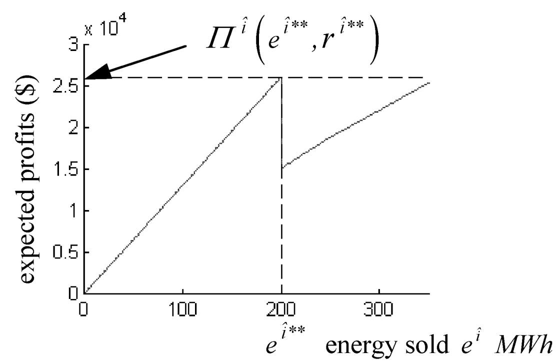

Fig. 4. Strategic seller's profits as a function of the energy sold by the strategic seller for a given system state.

withholds capacity to set prices at the market cap. This is true for all physical withholding cases[2].

The c.d.f.s of the margins $\underset{\sim}{R}$ and $\underset{\sim}{R}^M$ for test system A are shown in Figure 3. We observe that,

1. the distributions of $\underset{\sim}{R}^M$ and $\underset{\sim}{R}$ are identical for values of the resource availability margin less than -0.15;
2. the c.d.f. of $\underset{\sim}{R}^M$ is strictly larger than the c.d.f. of $\underset{\sim}{R}$ in the interval $[-0.15, 0.31]$;
3. for margins larger than 0.31, the distributions of $\underset{\sim}{R}^M$ and $\underset{\sim}{R}$ are identical.

The second bullet means that the probability of a loss of load

[2] If the offer cap has different values for different players, the objective for withholding capacity may be to set prices at the offer prices of a price taker.

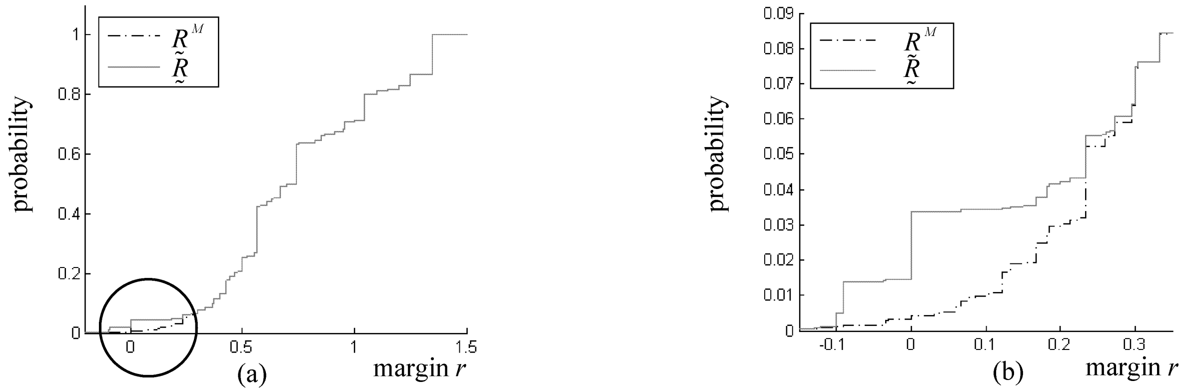

Fig. 5. Resource availability margin c.d.f. for test system A in a range of values of practical interest, (a); and a blowup of the circled region, (b).

event is strictly higher if market outcomes are taken into account than if they are not. In the cases characterized by this bullet, the strategic seller has strong incentives to physically withhold capacity since the reserves are tight. Such actions result in the distinct differences between the two distributions. The first and third bullets show that there are no incentives to physically withhold capacity when the resource availability margin is high, i.e., reserves are plentiful, or when the shortage is large. Note in Figure 3 that the probability of each available margin r is larger than or equal to the probability of the corresponding market margin r^M for positive margins, and smaller or equal for non-positive margins. This shows that if there is a reduction in the margin when we consider market forces, then the resulting margin will not be positive, i.e., the only reason for withholding capacity is to set prices at the market cap.

IV. Summary and Further Work

In this paper we have presented a framework for short-term resource adequacy which takes into account both the physical and market factors that impact reliability. We explicitly represented the strategic behavior of market participants to make the results realistic. The simulation studies indicate that the impacts of market factors on resource adequacy can be very significant. The work presented serves as a useful aid in the assessment of resource adequacy in electricity markets and in the design and enhancement of short-term resource adequacy programs.

The extensions of the work include the incorporation of demand responsiveness to price [9], multiple strategic sellers interaction, uncertainty in the strategic sellers' information, inter-hour relationships, transmission network effects and generation maintenance [15] into the models. Finally, the incorporation of models for generation investment would allow the study of long-term resource adequacy, which remains a critical need for the industry in the competitive environment.

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