A PROPOSED DESIGN FOR A SHORT-TERM RESOURCE ADECUACY PROGRAM

BY

PABLO ARIEL RUIZ

Ingeniero Electricista, Universidad Tecnológica Nacional – Santa Fe, 2002

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ABSTRACT

Resource adequacy is the ability of a system to meet the load at all times. A critical issue in the restructured electric utility industry is the capacity deficiency problems, with the events in the California electricity crisis in 2000–2001 being particularly notable. The capacity situation in California was further aggravated by the physical withholding of capacity. Several short-term resource adequacy programs have been established to address the issue. To date, the effectiveness of these programs is limited. In this thesis, we focus on the short-term resource adequacy problem in a competitive environment. The emphasis is on the understanding of the modeling needs and analytical aspects of the problem, and the development of requirements for an effective program.

We propose a design of a short-term resource adequacy program based on the specified capacity requirements formulated in terms of available capacity. This is the first proposed design with an explicit linkage between the associated economics and the reliability outcome. The design uses a *carrots and sticks* approach that gives incentives for providing capacity to markets and metes out penalties for nonperformance situations. The design allows the tuning of key design parameters including requirements formulation and penalty coefficient. The analysis of the proposed program shows that it results in improved reliability. We illustrate the impacts of the program using three different test systems. We test each system under a wide variety of conditions to study a large number of cases. In each case of each test system, the implementation of the design results in reliability improvements. Extensive sensitivity studies show that reduced total system costs can be attained with the proposed program when the tunable parameters are

judiciously selected. The design and analysis work of this thesis serves as a useful aid in the assessment and enhancement of short-term resource adequacy programs.

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CHAPTER 1

INTRODUCTION

In this chapter we set the stage for the work presented in the thesis. We start out with a definition of adequacy and provide a rationale for requiring a resource adequacy program in the design of electricity markets. Then we present a literature survey of publications relevant to the problems investigated, with an emphasis on the advantages and disadvantages of the resource adequacy programs that have been proposed and implemented. We outline the scope of this report and the contributions made, and provide a brief summary of the remainder of the thesis.

1.1 The Resource Adequacy Problem

The electric system is said to be *reliable* when consumers receive all the electricity they demand with the desired quality [1]. Electric system reliability is addressed by two basic aspects, *adequacy* and *security*. Adequacy is the ability of the system to meet the aggregate demand of electricity of all customers at all times, while security is the ability of the system to withstand sudden disturbances [1]. Adequacy is related to system planning and steady-state conditions; security is related to system operation, system stability, and transient conditions. We concentrate on the adequacy aspects of reliability.

Resource adequacy is concerned with meeting the adequacy target subject to supply and demand resource characteristics, load distribution, and player behavior in the market. The adequacy target is typically expressed in terms of the *loss of load probability* (*LOLP*) index [2] and a widely used value is one day in 10 years. When the time horizon is long, on the order of years, the decision variables are the installed capacities of the supply and demand resources. For a short-term focus on the order of months, any capacity additions/reductions are determined a priori, and so are independent of the decisions made during the period of interest. The only decision variables are therefore the offered/used capacities of the existing supply and demand resources. Our focus in this report is on short-term resource adequacy.

Adequacy is a system characteristic in that adequacy, when it exists, allows all consumers to have their loads met. Due to curtailment policies in place, the lack of adequacy may subject any consumer to loss of load events. Therefore, the benefits of having resource adequacy and the consequences of resource inadequacy are shared by all consumers. The economics literature refers to goods that no user can be prevented from using as *common-access goods* [3, p. 683]. Thus, adequacy is a common-access good.

In the market design of commodities other than electricity, there are no analogies to resource adequacy considerations. So, the question arises as to why the resource adequacy problem exists in electricity markets. The answer is related to the salient characteristics of electricity and its markets which make electricity a commodity unlike any other. Electricity is an essential commodity; modern society depends upon the use of electricity. In fact, regulatory requirements impose an *obligation to serve* on load serving entities [4].

The storage of electricity on a scale commensurate with market needs is not economically feasible today. Therefore, for all practical purposes, the generation of electricity cannot take place before the time of consumption. As such, electricity generation is the prototypical *just-in-time* manufacturing process, and electricity may be viewed as a highly *perishable* commodity. Consequently, electric energy cannot be delivered at time t if there is not enough available capacity to generate at time t. Hence, although the traded commodity in electricity markets is electric energy, the underlying product is available generation capacity.

The available capacity is inherently uncertain due to forced outages of generation units. On the demand-side, there is high demand variability and uncertainty in the forecasting of loads because of daily/seasonal consumption patterns, weather conditions, and general economic trends. These uncertainties are difficult to handle due to the long lead times — on the order of years — for adding new generating facilities. Furthermore, the financial risks associated with the construction of these facilities are very large because of the capital-intensive nature of those facilities. Moreover, the lack of real-time metering for most consumers leads to little demand responsiveness to price, and makes the issue of demand participation of little practical interest.

High demand variability and supply uncertainty make a just-in-time process, without storage, not optimal [5]. The infeasibility of storage leads us to conclude that in the case of electricity, the optimal solution is the existence of adequate capacity at all times, and it is of critical importance for the well being of society.

The radical transformations in the electric power industry have brought to prominence the adequacy problem. Prior to the restructuring in the 1990s, the electric energy industry was considered a natural monopoly [6]. An electric utility was granted a "franchise territory" to provide electric service, in return for which the utility had the obligation to serve all existing and future customers on a nondiscriminatory basis at tariff rates. Utilities were vertically integrated, i.e., a single owner was responsible for all phases of electricity generation, transmission, distribution, and customer service. The nature of regulation made the electric utility a cost plus enterprise, and utilities were allowed to earn up to their regulated rate of return of their investments. Thus, the utilities' interests were in making the investments which led to a steady stream of revenues. Utilities had no incentives to underinvest, perform inadequate maintenance, physically withhold capacity, or to take any other measures which would harm the system reliability.

Competitive markets were introduced to make the industry more efficient. In the 1990s, legislative and regulatory initiatives led to the establishment of competitive pool electricity markets. These markets are run by an independent entity named the Independent System Operator (ISO). The pool players sell and buy energy directly to and from the ISO by submitting sealed offers and bids to the ISO. Each offer specifies the amount of energy per hour the player is willing to sell and the minimum price per unit of energy it is willing to accept. Similarly, each bid specifies the amount of energy per hour the player is willing to buy and the maximum price per unit of energy it is willing to pay. Whenever the load is not responsive to price, the maximum price per unit of energy the buyer is willing to pay is set equal to a high price value. The ISO determines the successful bids and offers by maximizing the *social welfare* [7].

Under the new structure, there is little central planning, and generation, transmission, and distribution are functionally unbundled. Load serving entities (LSEs) remain saddled with the obligation to serve at regulated rates even though they may no longer own resources [4]. Since the generation resources are owned, by and large, by profit maximizing entities, such firms have incentives to take actions that increase their profits even when such actions may hurt system reliability. The negative impacts on reliability of such actions are due to strategic reductions in capacity offered to the market and/or deliberate strategies to not add new capacity. Examples of specific actions are:

- *physical capacity withholding* from the markets
- delay in performing required maintenance activities
- lack of investment in new capacity
- unit retirement / mothballing

The generation firms' profit maximization objectives may hurt system reliability for a number of reasons. The principal sources of revenue for such firms are sales in the hourly commodity (MWh) markets and the ancillary services markets. The uniform price payment for generation used in many markets results in the *hockey stick* shapes of the aggregated supply curves. When reserve capacity is tight, any decrease in capacity offered for generation results in attaining substantially higher market clearing prices. Such an outcome can be brought about through *physical* and *economic capacity withholding*. Physical withholding is the deliberate action of a generation unit controller to reduce the offered output below the available capacity, whereas economic withholding is the action of offering the generation output at offer prices above marginal costs [8, p. 454]. We illustrate physical and economic withholding in an energy market in Figure 1.1. The *supply* (*demand*) *curve* is the result of sorting the offers (bids) by price in increasing (decreasing) order and aggregating them in one curve.

Physical and economic withholding have identical impacts on a market clearing outcome in terms of the price and the quantity when the offer price of the unit economically withheld is sufficiently high and when the offered quantities in the market

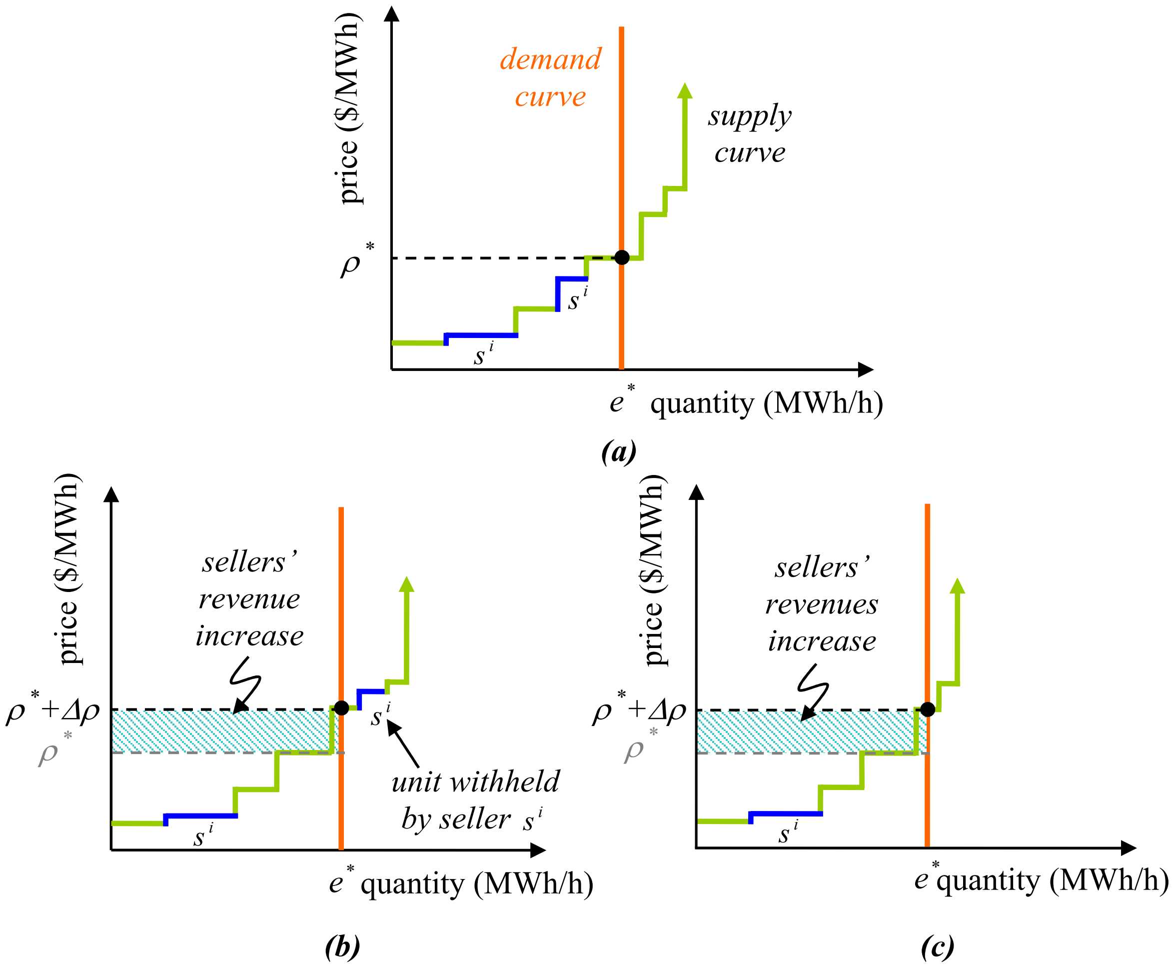
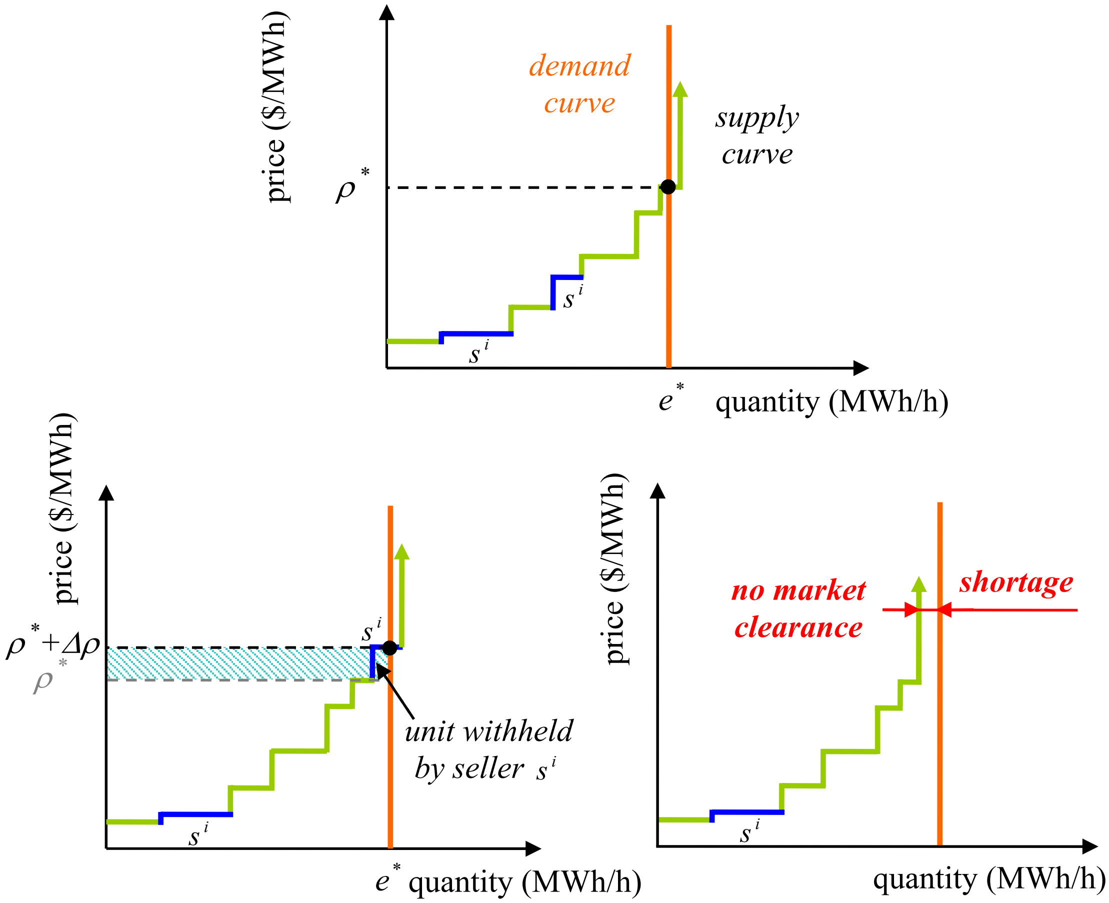


Figure 1.1: Physical and economic withholding in an energy market: (a) reference case with no withholding; (b) seller s^i economically withholds a unit; (c) seller s^i physically withholds the same unit.

are considerably larger than the demand. However, physical withholding has an additional important impact on the system. If capacity is scarce in the electricity market, physical capacity withholding may explicitly prevent the market from clearing due to a supply shortage. This shortage precludes some loads from being served regardless of their willingness to pay, thereby hurting system reliability. We illustrate the reliability impacts of physical withholding in Figure 1.2. The incentives for physically withholding are exacerbated when economic withholding is limited due to mitigation schemes, since from the point of view of a firm both types of withholding can serve a similar purpose.



(b) *(c)*

Figure 1.2: Reliability impacts of physical withholding: (a) reference case with no withholding; (b) seller s^i economically withholds a unit; there is no capacity shortage; (c) seller s^i physically withholds the same unit and there is capacity shortage.

In a competitive environment, an approach to directly solve the resource adequacy problem is through incentive/disincentive schemes to offer capacity in the electricity market. Such schemes have the objectives of making the profits of the generation firms depend on the system reliability, so that firms may have incentives to increase reliability or disincentives to decrease it. In the absence of explicit incentives (disincentives) for undertaking actions that may positively (negatively) impact reliability, a generation firm makes its decisions to protect its bottom line, completely independently of the reliability implications of such decisions. As a result, the system adequacy is left captive to the whims of profit maximizing entities. In these systems the LSEs and their consumers, which are directly impacted by reliability or lack thereof, do not have any tools to choose the service reliability that they need.

In fact, as physical capacity withholding, lack of investment in new supply sources, and early unit retirement are occurring in various jurisdictions with increased frequency, the issue of resource adequacy has become a critical concern for the industry and regulators [9]. Generation owners assert that they are not collecting sufficient revenues from their sales of MWh and services to recover their investment costs on a timely basis. As a result, several firms have applied to retire units which are critically important for system reliability [10, p. 27], [11]. Moreover, political uncertainties have deterred investment in new generation capacity. In some jurisdictions, physical capacity withholding was exercised to manipulate market prices, resulting in insufficient supply-side market participation[1] [14], [15]. These problems played a major role in the California electricity crisis in 2000 – 2001. The lack of resource adequacy presents a problem of present and critical importance and explicit steps are required to ensure that appropriate levels of capacity are provided around the clock in competitive electricity markets. We next examine the scope of the resource adequacy programs implemented in some jurisdictions and assess their ability to address this problem. We also provide a brief survey of the publications relevant to resource adequacy.

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1. A prohibition on physical and economic withholding was discarded by FERC [12, p. 32], explicitly stating that generation companies do not have the obligation to offer [13, p. 7] unless they acquire that obligation in a special contract.

1.2 Status of Programs to Address Resource Adequacy

The objective of any resource adequacy program is to ensure the system has the desired reliability level[2] using methods compatible with the rest of the market design. Contrary to the case of security, which is provided in the form of operating reserves, adequacy has not been effectively linked to economics. Hence, the specific goals of a program are to provide

- the reliability level required by the regional reliability council
- appropriate economic signals and incentives for adequacy
- effective means to curb the exercise of physical capacity withholding by generation entities
- a linkage between reliability improvements and market economics

The scope of the programs must effectively address such objectives by incorporating appropriate rules of the road to ensure that they can be achieved in practice.

There are two approaches for preventing the underprovision of any common-access good: *(i)* centralized regulation through taxation, and *(ii)* clear definition of property rights [3, p. 680]. The definition of property rights approach has not been used for adequacy because it is in conflict with nondiscrimination regulatory clauses. So, the typical approach to ensure system adequacy is to have a central authority impose a mandate for payments. This approach has been implemented in three different ways: through capacity payments, financial options requirements, and capacity requirements. We briefly describe each of these approaches and evaluate their advantages and shortcomings. More detailed descriptions of the approaches are provided in [17] and [18].

2. A discussion on the specification of reliability levels is provided in [16].

In the capacity payments implementation, administratively set hourly payments are given to all generators providing service [19]. In effect, the energy and ancillary service prices are increased, with payments being fixed or dependent on the estimated marginal outage costs. The rationale for capacity payments, a method for their evaluation, and some of the key limitations are discussed in [20]. While this approach administratively links adequacy and economics, no market mechanism is employed. The practical implementation of this approach has led to over-investment [10] and large-scale market gaming (pre-NETA UK design) [21]. The major advantage of the capacity payments approach is its simplicity.

In the option requirements implementation, LSEs are required to buy financial call options for energy [22], [23]. A financial call option for energy is a financial instrument that gives its holder the right but not the obligation to buy or sell a fixed amount of energy at a specified price on a given date [24]. The key assumption is that energy prices can be used as a proxy of reliability. This is not true in general, since prices may change due to other causes besides changes in the reliability levels; in particular, prices are highly dependent on the market design. Once we reject prices as a measure of reliability, the options requirement just turns into a mandate for price hedging.

Capacity requirements have been implemented in NYISO [25], ISO-NE [26], and PJM [27]. The requirements are based on the use of *ICAP* or *capacity credits*.[3] ICAP is a contract for one unit of capacity sold by an entity physically able to deliver energy and ancillary services. The key terms of the ICAP contract are:

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3. ICAP stands for installed capacity. Other terms used in the literature similar to ICAP are UCAP and ACAP, which stand for unforced capacity and available capacity, respectively.

- Duration: one month.

- Obligations on the sellers: to submit offers in the day-ahead markets for each hour of the month and deliver the services in the successful offers; the offers must be backed by the same (physical) capacity backing the ICAP. If the capacity is unavailable and the ISO is not notified, the seller is assessed a prespecified penalty; otherwise, the seller is not penalized.

- Obligations on the buyers: to pay the ICAP market clearing price.

The key idea is that for sellers to submit offers in the day-ahead markets and not physically withhold capacity, LSEs are required to purchase ICAP. An LSE b^n is required to have $(1+R)\ell^n$ MW of ICAP, where R is the required capacity margin and ℓ^n is the forecasted contribution of the LSE b^n to the system peak load. Once a month[4] there is an ICAP market where the LSEs buy ICAP to fulfill their requirements and the generation companies sell ICAP. ICAP markets use a double auction mechanism to set the market clearing price and quantity. While the resource adequacy requirements are imposed on the LSEs, the participation of the generation firms in the ICAP markets is purely voluntary. LSEs that buy less than they required ICAP must pay a preset penalty proportional to the amount of ICAP by which they fall short. The specified penalty on deficient LSEs acts as a *de facto* price cap on the ICAP market.

4. Shorter term capacity requirements, such as hourly requirements, have been proposed [28] and implemented in the early stages of the New England market. The high price volatility of the capacity product and large scale market manipulation led to the cancellation of the hourly requirement in ISO-NE in 2001 [29].

ICAP's underlying product is *unforced capacity* [25, p. J-1], which is essentially a forecast of the available capacity, and not actual available capacity. This is why ICAP sellers are not explicitly penalized if the unit is unavailable at any particular hour of the month. ICAP is tied to particular generating units. The amount of ICAP a given unit can provide is given by the expected available capacity of that unit.[5] As a unit becomes unavailable more frequently, the amount of ICAP the unit can provide decreases.

In [29], the authors present various considerations that need to be taken into account in the design of capacity requirements: forecasted loads, requirement timing, reserve requirements, and penalties on deficient LSEs and uncomplying generation firms. In [30] the authors reach the conclusion that *(i)* the planning and commitment horizon needs to be long enough to allow new investments (long-term side of adequacy), *(ii)* ICAP prices need to be determined competitively, *(iii)* one capacity market is better than multiple sequential markets for capacity, and *(iv)* an open auction format is desirable. These conclusions are taken into account in our work.

The major shortcomings of the capacity requirements approach are *(i)* ICAP's underlying product is expected capacity instead of actual capacity, even though actual capacity and not expected capacity provides the ability to meet the demand, and *(ii)* penalties can be ignored for all practical purposes. Thus, the only mechanism to encourage compliance is the decrease in the amount of ICAP the unit can provide in the following ICAP markets if the unit is physically withheld. The expression for the determination of the expected available capacity is fixed; therefore, this compliance mechanism is not easy to tune [25, p. J-1]. Moreover, this mechanism is indirect and

5. The expected available capacity is the best forecast of the available capacity that can be obtained with the existing information.

uncertain because the incentives to increase the ICAP sales are the revenues from the ICAP market, the revenues from the ICAP market are proportional to the ICAP market prices, and the ICAP market prices are uncertain.

Capacity requirements have been the preferred approach in all the U.S. electricity markets. The California Public Utilities Commission has decided to introduce resource adequacy requirements [31]; currently, there is no resource adequacy program in the California market. Moreover, two of the markets with capacity requirements are modifying them to account for the capacity providers' locations and to increase the time horizon to allow new investments. ISO-NE has received an order from FERC to implement the LICAP[6] program [32] and PJM Interconnection has proposed the Reliability Pricing Model program [33].

The implemented approaches have so far failed to provide a satisfactory solution to the resource adequacy problem. This is evidenced by the fact that most jurisdictions have been changing their resource adequacy program in the last five years. The adequacy problem remains an unsolved problem of critical interest to the industry. FERC has acknowledged the importance of the problem and the necessity to implement programs for resource adequacy in its SMD NOPR [9] and in the subsequent Wholesale Power Market Platform White Paper [34]. Thus, there is a need for the design of effective resource adequacy programs. Furthermore, there is a need for theoretical analysis to help in the design and implementation of resource adequacy programs. The lack of theoretical results is clearly exemplified in the discussion of LICAP design parameters, where most stakeholders expressed their belief in a particular parameter choice without giving a solid

6. LICAP stands for Locational ICAP.

rationale backed by theoretical analysis [35]. The aim in this work is to advance the state of the art in the design and analysis of resource adequacy programs.

1.3 Scope and Contribution of this Thesis

In this thesis, the emphasis is on the understanding of the modeling needs and analytical aspects of the short-term resource adequacy problem, and the development of requirements for an effective program. We propose a design of a short-term resource adequacy program for competitive electricity markets. This is the first proposed design with an explicit linkage between economics and reliability outcomes. The design uses a *carrots and sticks* approach that gives incentives for providing capacity to markets and metes out penalties for nonperformance situations. The design is based on the specified capacity requirements which the program formulates in terms of available capacity. The analysis of the proposed design shows that the program improves system reliability. We present a simple implementation of the proposed design to allow the assessment of the resulting short-term resource adequacy. The analysis provided gives a good basis for the selection of appropriate parameters of the proposed program.

We assess the effectiveness of the proposed design with simulation results on three distinct test systems. We test each system under a wide variety of conditions to study a large number of cases. In each case of each test system, the implementation of the design results in reliability improvements. Extensive sensitivity studies show that improved reliability and reduced total system costs can be attained with the proposed program when the tunable parameters are judiciously selected.

The rest of this report is organized as follows. In Chapter 2 we provide the analytical basis for the analysis of short-term resource adequacy. In Chapter 3 we introduce and analyze the proposed short-term resource adequacy program design. We present and discuss the results of the simulation studies in Chapter 4. Chapter 5 summarizes the key results of our studies and points out directions for future work.

This thesis also has four appendices to provide a self-contained documentation of the work. Appendix A provides a summary of the acronyms and the notation used in this thesis. In Appendix B we give an algorithm used by the generation firms in our simulations to choose their offering strategy. Appendix C discusses the determination of the capacity credits costs. We provide a complete description of the three test systems used in the simulation studies in Appendix D.

CHAPTER 2

MODELING ASPECTS

The analysis of short-term resource adequacy requires the modeling of the load demand and the generation resources for reliability evaluation, the electricity markets and each market player's behavior for the incorporation of market outcome impacts on reliability, and the resource adequacy program that is in place. These models, together with the appropriate reliability and market metrics, are used to evaluate the performance of a resource adequacy program. In this chapter we describe the set of models and metrics used in such an evaluation. The model of the seller behavior presented in this chapter is new and so it constitutes a contribution of this thesis.

This chapter contains six sections. We describe the modeling needs in short-term resource adequacy and give an overview of the models we use for the analysis of the resource adequacy problem in Section 2.1. In Section 2.2, we present the models of the resources—generation and demand—and discuss reliability evaluation without taking into account market outcomes. In Sections 2.3 and 2.4 we present the market and the sellers' models, respectively; these models provide the market outcomes that are incorporated in the reliability evaluation. In Section 2.5, we discuss the impacts of seller behavior on reliability, and evaluate the metrics taking into account market outcome information. We present the modeling of resource adequacy programs in Section 2.6.

2.1 Modeling Overview

We define one hour as the smallest indecomposable unit of time. A resolution of one hour allows the representation of short-term events of interest such as intraday demand and price variability. We choose the time horizon of interest to be H hours. Typically, H is the number of hours in a month and we use the index $h = 1, 2, ..., H$ for these hours. We focus on a single hour h to explain the problem statement.

The problem statement uses the time frame as presented in Figure 2.1. Before the day-ahead markets occur, the design of the resource adequacy program is made available to the market players, the hour h demand is forecasted by the LSEs, and the available capacities are forecasted by the generation firms. The forecast of the available generation capacities is assumed to be equal to the values taken by the available capacities, and so all uncertainty on the supply side from the day-ahead on is neglected.[1] The forecasts and resource adequacy program information are used by the market players in their offer/bid preparations for the day-ahead electricity market. In the hour h, the demand and available capacity are determined, and reserves are dispatched if needed. Whenever the demand is larger than the total capacity offered in the day-ahead market, there is a loss of load event of magnitude equal to the difference between the load and the capacity offered.[2] The settlement of the energy, reserves, and resource adequacy program payments is performed, typically, 28 days after the fact.

In the remainder of this section we give an overview of the main modeling assumptions made in this report. We consider an isolated system with no interconnections to any other system. We assume that this isolated system has a transmission network which has ample transfer capability for accommodating all the desired market outcomes. As such, we assume that there is no congestion and ignore all other network

1. This simplifying assumption can be thought of as including all the available capacity uncertainty at the time the day-ahead market takes place in the load demand uncertainty; the rationale is that both supply and demand uncertainties are taken care of in the same manner: procuring operating reserves [1, p. 22].
2. In this work, we ignore the effects of the transmission network.

considerations. In effect, we view all the generating buses and load buses as constituting a mass generation and a mass load at a single bus.

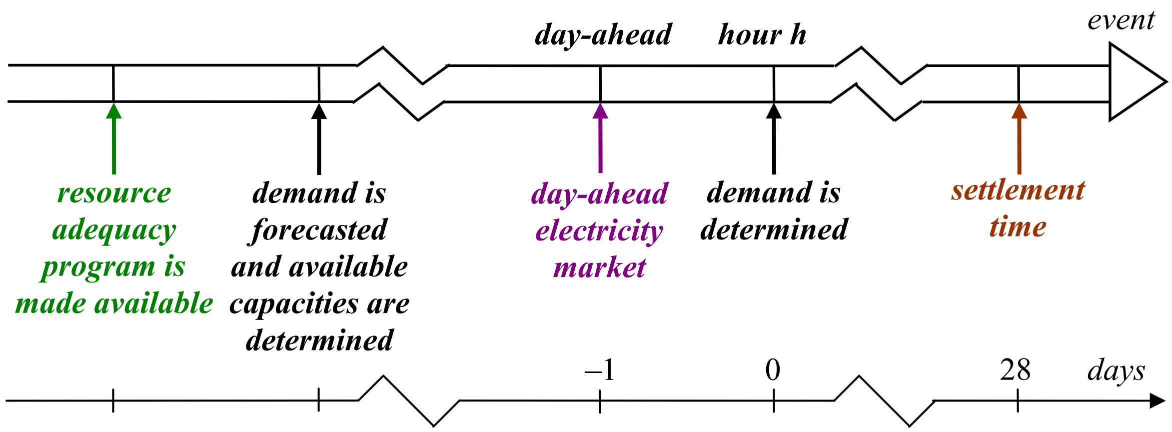

Figure 2.1: Time frame.

We concentrate on the typical centralized pool market structure widely adopted in North American markets and we ignore all transactions done outside the market. The centralized pool markets are run by the independent system operator (ISO). The pool sellers indicate their willingness to sell to the ISO by submitting sealed offers specifying the quantities and asking price. At the same time, the pool buyers submit sealed bids to indicate their willingness to buy from the ISO. From the set of submitted offers and bids, the ISO determines the set of successful offers and bids and the market clearing prices. All the trades in these markets are between a pool player and the ISO.

We further assume the energy and reserves markets are joined together as the single *combined energy and reserves market* (*CERM*) to avoid gaming opportunities and increase market efficiency [36, p. 121], [37]. We assume the sellers in the CERM are generation firms, i.e., entities with actual physical resources, and the buyers are the LSEs.

The CERM is therefore a physical market.[3] Sellers' offers are backed by deliverable capacity and buyers bids have the purpose of fulfilling the needs of a load.

We assume the demand is independent of the energy and reserves market prices of the hour *h*. Market prices are limited by the administratively set market price caps $\overline{\rho}_e$ and $\overline{\rho}_r$ for energy and reserves, respectively. We assume the reserves bids are sufficient to cover any variation in the hour *h* demand with respect to the demand forecast.

Sellers are assumed to be risk neutral and profit maximizing firms, and they consider physical and economic withholding feasible strategies in the CERM. Sellers submit offers to the CERM consisting of quantities and the associated offer prices. The sellers' offer prices are constrained by offer price caps. These offer price caps limit the feasibility of exercising economic withholding, and so sellers may have the incentive to physically withhold.

2.2 Reliability Evaluation

In this section we describe the models of the physical system resources on the supply and demand sides that are used for reliability evaluation together with the reliability metrics.

The set of LSEs is denoted by

$$\mathbb{B} = \left\{ b^1, b^2, ..., b^B \right\}. \tag{2.1}$$

The aggregated demand of real power of all the LSEs, the system *load demand*, in an arbitrary hour in the period of interest is modeled by the random variable (r.v.) $\underset{\sim}{L}$. The

3. For a discussion of such markets, see for example [38, p. 2-11]. Typically, such markets take place in the day-ahead of the hour of interest *h* [38, p. 1-6].

system demand as expressed is independent of the hour. However, the demand in different hours may have very different characteristics, e.g., *peak* hour vs. *valley* hour in the same day, weekend hour vs. week day hour for the same time of the day, etc. To allow the representation of these differences, we define D classes of demands on the basis of certain specified demand levels. Correspondingly, we partition the set of all hours in the month into the nonoverlapping subsets $\mathbb{T}_1, \mathbb{T}_2, ..., \mathbb{T}_D$, with

$$\bigcup_{d=1}^{D} \mathbb{T}_d = \{1, 2, ..., H\} .$$

The elements of $\mathbb{T}_d$ are the hours with a demand class d. The number of hours in $\mathbb{T}_d$ is denoted by H_d, and so

$$\sum_{d=1}^{D} H_d = H .$$

All hours in each demand class set have uniform demand characteristics. Throughout this chapter, our focus is on a snapshot of the system in hour $h \in \mathbb{D}_d$, $d = 1, 2, ..., D$.

We model the system load demand for the hour $h \in \mathbb{D}_d$ by the r.v. $\underset{\sim}{L}_d$

$$\underset{\sim}{L}_d = \underset{\sim}{L} \Big| h \in \mathbb{D}_d \; . \tag{2.2}$$

This r.v. is the sum of a deterministic quantity ℓ_d and a r.v. $\Delta \underset{\sim}{L}_d$ which models the uncertainty in the load demand,

$$\underset{\sim}{L}_d = \ell_d + \Delta \underset{\sim}{L}_d \, . \tag{2.3}$$

The distribution of $\Delta \underset{\sim}{L}_d$ is given by

$$\Delta \underset{\sim}{L}_d = \begin{cases} 0 & \text{with probability } p_d \\ \delta_d > 0 & \text{with probability } \left(1-p_d\right). \end{cases} \tag{2.4}$$

The cumulative distribution function (c.d.f.) of $\underset{\sim}{L}_d$ is thus given by

$$F_{\underset{\sim}{L}_d}\left(x\right) = \boldsymbol{P}\left\{\underset{\sim}{L}_d \le x\right\} = \begin{cases} 0 & x < \ell_d \\ p_d & \ell_d \le x < \ell_d + \delta_d \\ 1 & \ell_d + \delta_d \le x. \end{cases}$$

The *system peak load* ℓ^p is defined as the maximum value $\underset{\sim}{L}$ can take

$$\ell^p = \max_{1 \le d \le D}\left\{\ell_d + \delta_d\right\}. \tag{2.5}$$

The *system base load* ℓ^m is defined as the minimum value $\underset{\sim}{L}$ can take

$$\ell^m = \min_{1 \le d \le D}\left\{\ell_d\right\}. \tag{2.6}$$

We can express $\underset{\sim}{L}$ in terms of the $\underset{\sim}{L}_d$'s by

$$\boldsymbol{P}\left\{\underset{\sim}{L} = \underset{\sim}{L}_d\right\} = \frac{H_d}{H} \tag{2.7}$$

Thus, the c.d.f. of $\underset{\sim}{L}$ is given by

$$F_{\underset{\sim}{L}}\left(x\right) = \sum_{d=1}^{D} F_{\underset{\sim}{L}_d}\left(x\right)\frac{H_d}{H}.$$

The *expected energy demanded* $\mathcal{E}$, expressed in MWh, is given by

$$\mathcal{E} \triangleq H\,\boldsymbol{E}\left\{\underset{\sim}{L}\right\} = H\sum_{d=1}^{D}\frac{H_d}{H}\boldsymbol{E}\left\{\underset{\sim}{L}_d\right\}. \tag{2.8}$$

The set of generation firms is denoted by

$$\mathbb{S} = \left\{s^1, s^2, \ldots, s^S\right\}. \tag{2.9}$$

Each firm s^i, $i = 1, 2, ..., S$ has one or more generation units. The *capacity* of the generator *j* of firm s^i in MW is denoted by g_j^i, the capacity of firm s^i is denoted by

$$g^i = \sum_{j=1}^{G^i} g_j^i , \tag{2.10}$$

where G^i is the number of generators of firm s^i. The system capacity is denoted by

$$g = \sum_{i=1}^{S} g^i = \sum_{i=1}^{S} \sum_{j=1}^{G^i} g_j^i . \tag{2.11}$$

The *available capacity* is the capacity that can be used to provide service. The available capacity of the generator j of firm s^i is modeled by the r.v. $\underset{\sim}{A}_j^i$,

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

Each parameter a_j^i is called the *availability* of the unit *j* of seller s^i. The available capacity of firm s^i is denoted by

$$\underset{\sim}{A}^i = \sum_{j=1}^{G^i} \underset{\sim}{A}_j^i$$

and the total available capacity in the system is modeled by the random variable

$$\underset{\sim}{A} = \sum_{i=1}^{S} \underset{\sim}{A}^i = \sum_{i=1}^{S} \sum_{j=1}^{G^i} \underset{\sim}{A}_j^i .$$

A value taken by the available capacity $\underset{\sim}{A}_j^i$ is denoted by α_j^i, and so α_j^i is either g_j^i or 0. A value taken by $\underset{\sim}{A}^i$ is denoted by α^i, and a value taken by $\underset{\sim}{A}$ is denoted by α.

We next focus on the evaluation of system reliability. Reliability evaluation is based on the assumption that all the demand is served whenever the available capacity $\underset{\sim}{A}$ is at least as large as the demand $\underset{\sim}{L}$. This is clearly a probabilistic event. We use the following values to reflect the probabilistic nature of the event: the *resource availability margin*, the *loss of load probability*, the *expected unserved energy*, and the *expected outage costs.* The resource availability margin $\underset{\sim}{R}$ is defined as the difference between the available capacity and the demand, with respect to the demand magnitude,

$$\underset{\sim}{R} = \Omega\left(\underset{\sim}{A},\underset{\sim}{L}\right) \triangleq \frac{\underset{\sim}{A}-\underset{\sim}{L}}{\underset{\sim}{L}} = \frac{\underset{\sim}{A}}{\underset{\sim}{L}} - 1 . \tag{2.12}$$

The resource availability margin provides a relative measure of the hourly available reserves in the system, and as such, it is a random variable. The function $\Omega(\cdot,\cdot)$ takes values in $\left[-1, \frac{g}{\ell^m} - 1\right]$.

The loss of load probability is defined as

$$LOLP = \boldsymbol{P}\left\{\underset{\sim}{L} > \underset{\sim}{A}\right\} . \tag{2.13}$$

The *LOLP* explicitly incorporates the uncertainty in both the demand and supply, but it does not take into account the magnitude of the shortfall of available capacity or any economic aspect. The expected unserved energy is defined as

$$\mathscr{U} = H \cdot \boldsymbol{E}\left\{\underset{\sim}{L} - \underset{\sim}{A} \middle| \underset{\sim}{L} > \underset{\sim}{A}\right\} LOLP . \tag{2.14}$$

Uncertainty in demand and supply, and the magnitude of shortages, are taken into full account in the computation of $\mathscr{U}$, but no pricing/costing information is considered. We finally introduce the expected outage costs $\mathscr{C}_o$ associated with $\mathscr{U}$. In $\mathscr{C}_o$, the assessment of the economic impacts on consumers of the expected outages are considered using an average value *w* (in \$/MWh) that consumers assign to the electricity not supplied, called their *value of lost load* [39]. Thus, the expression for $\mathcal{C}_o$ is

$$\mathcal{C}_o = wH \cdot \boldsymbol{E}\left\{ \underset{\sim}{L} - \underset{\sim}{A} \middle| \underset{\sim}{L} > \underset{\sim}{A} \right\} LOLP \,. \tag{2.15}$$

The outage costs have the advantage of having units of dollars and it is well suited for economic analysis. The problem $\mathcal{C}_o$ has is the difficulty in determining *w* with up-to-date information.

2.3 The CERM

Reliability evaluation is based on the physical characteristics of the resources and does not consider market outcomes. However, market outcomes may have large impacts on reliability. To incorporate market information in the reliability evaluation, we need models of the market and the behavior of the market players. We introduce the market model in this section and the models of the seller behavior in next section.

We focus on the CERM for the hour $h \in \mathbb{D}_d$. The CERM consists of buyers and sellers; the set of buyers is the set of LSEs $\mathbb{B} = \left\{ b^1, b^2, ..., b^B \right\}$ and the set of sellers is the set of generation firms $\mathbb{S}$. The bids submitted by the buyers consist only of the amount of MWh of energy requested to satisfy the buyer's demand, and not on the maximum prices the buyers are willing to pay. The aggregated market demand for energy is the quantity ℓ_d in MWh, and the aggregated market demand for reserves is the quantity $\varepsilon_d \delta_d$ in MW, where $\varepsilon_d \geq 1$ is fixed. Both demanded quantities are fixed and so they are independent of the market prices.

Sellers submit their offers using a block format. The k-*th block offer*[4] from generator *j* of seller s^i is the four-tuple Γ_j^{ik} characterized by the energy and reserves *offer prices* σ_j^{ik} and ς_j^{ik}, respectively, and the block and reserve *capacities* κ_j^{ik} and π_j^{ik}, respectively,

$$\Gamma_j^{ik} = \left\{ \sigma_j^{ik}, \varsigma_j^{ik}, \kappa_j^{ik}, \pi_j^{ik} \right\}.$$

The offer prices $\sigma_j^{ik} \in \left[0, \bar{\rho}_e^i\right]$ and $\varsigma_j^{ik} \in \left[0, \bar{\rho}_r^i\right]$ respectively indicate the price at which the seller is willing to sell each unit of energy ($/MWh) and reserves ($/MW) of the block. The upper limits $\bar{\rho}_e^i \le \bar{\rho}_e$ and $\bar{\rho}_r^i \le \bar{\rho}_r$ on the offer prices are termed offer price caps for seller s^i, and their purpose is to limit the exercise of economic withholding by each seller.[5] The capacity κ_j^{ik} of the block indicates the maximum amount of reserves and energy that seller s^i offers to sell from its generator *j* at the prices σ_j^{ik} and ς_j^{ik} in the CERM. The capacity $\pi_j^{ik} \le \kappa_j^{ik}$ indicates the maximum amount of reserves that seller s^i offers to sell from its generator *j* at the price ς_j^{ik} in the CERM. We denote by e_j^{ik} (r_j^{ik}) the amount of energy (reserves) sold to the ISO by seller s^i from the offered block *k* of its unit *j*.

Each seller s^i submits an offer consisting of β block offers. We represent the block offers characteristics with the vectors $\underline{\sigma}_j^i \triangleq \left[\sigma_j^{i1}, \sigma_j^{i2}, \ldots, \sigma_j^{i\beta}\right]'$, $\underline{\varsigma}_j^i \triangleq \left[\varsigma_j^{i1}, \varsigma_j^{i2}, \ldots, \varsigma_j^{i\beta}\right]'$, $\underline{\kappa}_j^i \triangleq \left[\kappa_j^{i1}, \kappa_j^{i2}, \ldots, \kappa_j^{i\beta}\right]'$, and $\underline{\pi}_j^i \triangleq \left[\pi_j^{i1}, \pi_j^{i2}, \ldots, \pi_j^{i\beta}\right]'$. We also

4. The block offers may be independent of the physical characteristics of a unit.
5. This scheme is a simplified model of the one used by NYISO [40] for market power mitigation.

represent the quantities sold in the vectors $\underline{\boldsymbol{e}}_j^{\,i} \triangleq \left[e_j^{i1}, e_j^{i2}, \ldots, e_j^{i\beta}\right]'$ and $\underline{\boldsymbol{r}}_j^{\,i} \triangleq \left[r_j^{i1}, r_j^{i2}, \ldots, r_j^{i\beta}\right]'$. The total energy and reserves provided by generator j of seller i, denoted e_{jT}^{i} and r_{jT}^{i}, are given by $e_{jT}^{i} \triangleq \underline{\mathbf{1}}'\underline{\boldsymbol{e}}_j^{\,i}$ and $r_{jT}^{i} \triangleq \underline{\mathbf{1}}'\underline{\boldsymbol{r}}_j^{\,i}$, where $\underline{\mathbf{1}}$ denotes the vector with all elements ones of the appropriate dimension.

The offer Γ^i of seller s^i consists of the collection of offers from its generation units, $\Gamma^i = \left\{\Gamma_j^{ik}\right\}_j^k$. We order the vectors of offer prices and capacities from each generator in the vectors $\underline{\boldsymbol{\sigma}}^{\,i} \triangleq \left[\underline{\boldsymbol{\sigma}}_1^{\,i\,\prime}, \underline{\boldsymbol{\sigma}}_2^{\,i\,\prime}, \ldots, \underline{\boldsymbol{\sigma}}_{G^i}^{\,i\,\prime}\right]'$, $\underline{\boldsymbol{\varsigma}}^{\,i} \triangleq \left[\underline{\boldsymbol{\varsigma}}_1^{\,i\,\prime}, \underline{\boldsymbol{\varsigma}}_2^{\,i\,\prime}, \ldots, \underline{\boldsymbol{\varsigma}}_{G^i}^{\,i\,\prime}\right]'$, $\underline{\boldsymbol{\kappa}}^{\,i} \triangleq \left[\underline{\boldsymbol{\kappa}}_1^{\,i\,\prime}, \underline{\boldsymbol{\kappa}}_2^{\,i\,\prime}, \ldots, \underline{\boldsymbol{\kappa}}_{G^i}^{\,i\,\prime}\right]'$, and $\underline{\boldsymbol{\pi}}^{\,i} \triangleq \left[\underline{\boldsymbol{\pi}}_1^{\,i\,\prime}, \underline{\boldsymbol{\pi}}_2^{\,i\,\prime}, \ldots, \underline{\boldsymbol{\pi}}_{G^i}^{\,i\,\prime}\right]'$. We also order the vectors of quantities sold and form the vectors $\underline{\boldsymbol{e}}^{\,i} \triangleq \left[\underline{\boldsymbol{e}}_1^{\,i\,\prime}, \underline{\boldsymbol{e}}_2^{\,i\,\prime}, \ldots, \underline{\boldsymbol{e}}_{G^i}^{\,i\,\prime}\right]'$ and $\underline{\boldsymbol{r}}^{\,i} \triangleq \left[\underline{\boldsymbol{r}}_1^{\,i\,\prime}, \underline{\boldsymbol{r}}_2^{\,i\,\prime}, \ldots, \underline{\boldsymbol{r}}_{G^i}^{\,i\,\prime}\right]'$. The total energy and reserves provided by seller s^i, denoted e_T^i and r_T^i, are given by $e_T^i \triangleq \underline{\mathbf{1}}'\underline{\boldsymbol{e}}^{\,i}$ and $r_T^i \triangleq \underline{\mathbf{1}}'\underline{\boldsymbol{r}}^{\,i}$. Also, the capacity offered to the CERM by seller s^i is denoted by $\kappa_T^i \triangleq \underline{\mathbf{1}}'\underline{\boldsymbol{\kappa}}^{\,i}$.

We order the offer prices and capacities of all sellers in the vectors $\underline{\boldsymbol{\sigma}} \triangleq \left[\underline{\boldsymbol{\sigma}}^{1\prime}, \underline{\boldsymbol{\sigma}}^{2\prime}, \ldots, \underline{\boldsymbol{\sigma}}^{S\prime}\right]'$, $\underline{\boldsymbol{\varsigma}} \triangleq \left[\underline{\boldsymbol{\varsigma}}^{1\prime}, \underline{\boldsymbol{\varsigma}}^{2\prime}, \ldots, \underline{\boldsymbol{\varsigma}}^{S\prime}\right]'$, $\underline{\boldsymbol{\kappa}} \triangleq \left[\underline{\boldsymbol{\kappa}}^{1\prime}, \underline{\boldsymbol{\kappa}}^{2\prime}, \ldots, \underline{\boldsymbol{\kappa}}^{S\prime}\right]'$, and $\underline{\boldsymbol{\pi}} \triangleq \left[\underline{\boldsymbol{\pi}}^{1\prime}, \underline{\boldsymbol{\pi}}^{2\prime}, \ldots, \underline{\boldsymbol{\pi}}^{S\prime}\right]'$. We also order the sold quantities as $\underline{\boldsymbol{e}} \triangleq \left[\underline{\boldsymbol{e}}^{1\prime}, \underline{\boldsymbol{e}}^{2\prime}, \ldots, \underline{\boldsymbol{e}}^{S\prime}\right]'$ and $\underline{\boldsymbol{r}} \triangleq \left[\underline{\boldsymbol{r}}^{1\prime}, \underline{\boldsymbol{r}}^{2\prime}, \ldots, \underline{\boldsymbol{r}}^{S\prime}\right]'$. The total capacity offered in the market is denoted by $\kappa_T \triangleq \underline{\mathbf{1}}'\underline{\boldsymbol{\kappa}}$.

The ISO collects the sellers' offers and determines the set of successful offers and the market prices. The ISO's decision is based on the objective of maximizing the *social welfare* $\mathscr{S}_d(\cdot,\cdot)$,

$$\mathscr{S}_d(\underline{\boldsymbol{e}},\underline{\boldsymbol{r}}) \triangleq w_e\left(\ell_d + (1-p_d)\delta_d\right) + w_r\varepsilon_d\delta_d - \left(\underline{\boldsymbol{\sigma}}'\underline{\boldsymbol{e}} + \underline{\boldsymbol{\varsigma}}'\underline{\boldsymbol{r}}\right), \tag{2.16}$$

where $w_e > \overline{\rho}_e$ and $w_r > \overline{\rho}_r$ are estimates of the benefits of the demand per unit of energy and reserves. As the demand for energy and reserves is fixed, the benefit term

$$w_e\left(\ell_d + (1-p_d)\delta_d\right) + w_r\varepsilon_d\delta_d$$

is constant, and so maximizing $\mathscr{S}_d(\cdot,\cdot)$ is equivalent to minimizing the costs $\mathscr{C}(\cdot,\cdot)$,

$$\mathscr{C}(\underline{\boldsymbol{e}},\underline{\boldsymbol{r}}) \triangleq \underline{\boldsymbol{\sigma}}'\underline{\boldsymbol{e}} + \underline{\boldsymbol{\varsigma}}'\underline{\boldsymbol{r}}. \tag{2.17}$$

The outcomes of the market must satisfy the CERM supply-demand balance for energy and reserves. Consequently, the decision-making process involves the solution of the following linear optimization problem,

$$(CERM)\begin{cases} \min\limits_{\underline{\boldsymbol{e}},\underline{\boldsymbol{r}}} \ \mathscr{C}(\underline{\boldsymbol{e}},\underline{\boldsymbol{r}}) \\ s.t. \\ \qquad \underline{\mathbf{1}}'\underline{\boldsymbol{e}} = \ell_d \\ \qquad \underline{\mathbf{1}}'\underline{\boldsymbol{r}} \geq \varepsilon_d\delta_d \\ \qquad \underline{\boldsymbol{e}} + \underline{\boldsymbol{r}} \leq \underline{\boldsymbol{\kappa}} \\ \qquad \underline{\boldsymbol{r}} \leq \underline{\boldsymbol{\pi}} \\ \qquad \underline{\boldsymbol{e}},\underline{\boldsymbol{r}} \geq \underline{\boldsymbol{0}}. \end{cases} \tag{2.18}$$

The optimal solution $\left(\underline{\boldsymbol{e}}^*,\underline{\boldsymbol{r}}^*\right)$ of this problem determines the sales of the sellers. In the case the market does not clear, i.e., this problem is infeasible, and equality constraints are not satisfied, the demand for energy is given priority over the demand for reserves.

Prices are determined ex-post, when the random component of the load demand $\Delta \underset{\sim}{L}_d$ is determined, and they are equal to the asking price of the most expensive block providing service if (2.18) is feasible. Whenever (2.18) is infeasible, the prices are determined from Table 2.1. Sellers (buyers) are paid (pay) a uniform price for providing the same service. Providers of reserves receive the energy price in addition to the reserve price whenever they are asked to produce energy as well.

Table 2.1: Energy and reserves prices

<table>
<tr><th>condition</th><th>$\Delta \underset{\sim}{L}_d$</th><th>$\rho_e^*$</th><th>$\rho_r^*$</th><th>description</th></tr>
<tr><td rowspan="2">$\kappa_T \le \ell_d$</td><td>0</td><td>$\bar{\rho}_e$</td><td rowspan="2">-</td><td rowspan="2">energy shortfall</td></tr>
<tr><td>δ_d</td><td>$\bar{\rho}_e$</td></tr>
<tr><td rowspan="2">$\ell_d < \kappa_T \le \ell_d + \delta_d$
or
$\kappa_T > \ell_d + \delta_d$,
$\pi_T \le \delta_d$</td><td>0</td><td>asking price for energy of the most expensive block with $e_j^{ik*} > 0$</td><td rowspan="2">$\bar{\rho}_r$</td><td rowspan="2">reserves shortfall, and energy shortfall if $\Delta \underset{\sim}{L}_d = \delta_d$</td></tr>
<tr><td>δ_d</td><td>$\bar{\rho}_e$</td></tr>
<tr><td rowspan="2">$\kappa_T > \ell_d + \delta_d$,
$\delta_d < \pi_T \le \varepsilon_d \delta_d$
or
$\ell_d + \delta_d < \kappa_T \le \ell_d + \varepsilon_d \delta_d$,
$\pi_T > \varepsilon_d \delta_d$</td><td>0</td><td>asking price for energy of the most expensive block with $e_j^{ik*} > 0$</td><td rowspan="2">$\bar{\rho}_r$</td><td rowspan="2">reserves shortfall</td></tr>
<tr><td>δ_d</td><td>asking price for energy of the most expensive block with either $e_j^{ik*} > 0$ or $r_j^{ik*} > 0$</td></tr>
<tr><td rowspan="2">$\kappa_T > \ell_d + \varepsilon_d \delta_d$,
$\pi_T > \varepsilon_d \delta_d$</td><td>0</td><td>asking price for energy of the most expensive block with $e_j^{ik*} > 0$</td><td rowspan="2">asking price for reserves of the most expensive block with $r_j^{ik*} > 0$</td><td rowspan="2">no shortfall</td></tr>
<tr><td>δ_d</td><td>asking price for energy of the most expensive block with either $e_j^{ik*} > 0$ or $r_j^{ik*} > 0$</td></tr>
</table>

In the medium term there is uncertainty on the sellers' offers to the CERM, and so the optimal value of $\mathscr{C}(\cdot,\cdot)$ is modeled as the r.v. $\underset{\sim}{C}$. The *service costs* $\mathcal{C}_s$ are defined as

$$\mathcal{C}_s \triangleq H\, \boldsymbol{E}\{\underset{\sim}{C}\}. \tag{2.19}$$

The service costs are a measure of the revenues the sellers receive and the payments the set of LSEs make in the period of *H* hours, and they provide a measure of the expected market efficiency in the period. An increase in $\mathcal{C}_s$ implies a decrease in market efficiency, and a decrease in $\mathcal{C}_s$ implies a market efficiency improvement.

2.4 The Sellers' Behavior

In this section, we formulate the sellers offering problem in the CERM subject to an offer price cap. The published literature tackles the seller problem without consideration of offer price caps [41], [42]. The formulation of this model has not been reported in the electricity literature, and thus is a contribution of this thesis.

Sellers are assumed to be profit maximizing and risk neutral firms. The profit maximizing assumption leads each firm to maximize its profits. Under risk neutrality, a firm maximizes its expected profits in the presence of uncertainty. Typically, this goal is met by physical and/or economic withholding. We assume that economic withholding is preferred over physical withholding whenever both behaviors result in the same expected profits.

We consider two types of sellers, *price takers* and *price setters* [3, p. 46]. We use the terminology *strategic seller* instead as price setter, as is usually done in the power systems literature [36, p. 40]. Price takers are players which cannot affect the market price, while strategic sellers are players which have the ability to affect the market price

[3, p. 46]. Thus, price takers are "passive" players whose CERM actions have no impact on reliability, and strategic sellers are "active" players whose decisions may impact reliability.

The production costs of each generator are modeled as a piece-wise linear function of the output of the generator. The production costs comprise the costs that are proportional to the output of the generator, such as fuel costs and variable operation and maintenance costs. All fixed and startup costs are ignored. The incremental or *marginal* production costs are then piece-wise constant. We ignore the minimum operating capacity constraint and the minimum up-time and down-time constraints of all generators.

Price takers determine their offering strategies as if they could not affect the market clearing price [8, p. 451]. Consider the physical block *k* of unit *j* with marginal production costs f_j^{ik} owned by seller s^i with a price taker behavior. Price taker s^i offers all the capacity of such block in the CERM because the optimal offering strategy of a price taker is to offer all its capacity at marginal costs [37], and the energy offer price is

$$\sigma_j^{ik} = \left(1+\zeta_j^{ik}\right) f_j^{ik}, \tag{2.20}$$

where $\zeta_j^{ik} \geq 0$ is such that the product $\zeta_j^{ik} f_j^{ik}$ covers the marginal costs which are not due to production costs, e.g., transaction costs. We neglect any production costs of reserves, and so the reserve offer price of the block is given by

$$\varsigma_j^{ik} = \zeta_j^{ik} f_j^{ik}. \tag{2.21}$$

Expressions (2.20) and (2.21) are valid whenever $\bar{\rho}_e^i > \left(1+\zeta_j^{ik}\right) f_j^{ik}$ and $\bar{\rho}_r^i > \zeta_j^{ik} f_j^{ik}$, which we assume hold.

Strategic sellers determine their offering strategies taking into account the impacts of their offer in the market clearing price. For simplicity, we assume that there is only one strategic seller,[6] denoted seller $s^{\hat{i}}$. The total cost for seller $s^{\hat{i}}$ as a function of the MWh (MW) output is denoted by $\chi_e^{\hat{i}}(\cdot)$ ($\chi_r^{\hat{i}}(\cdot)$).

The strategic seller's decision variables are the expected amount $e^{\hat{i}}$ of energy and the expected reserves $r^{\hat{i}}$ that seller $s^{\hat{i}}$ sells in the CERM. The two-tuple $\left(e^{\hat{i}}, r^{\hat{i}}\right)$ is feasible if and only if there exists an offer $\Gamma^{\hat{i}} = \left\{\Gamma_j^{\hat{i}k}\right\}_j^k$ such that

$$e_T^{\hat{i}} = e^{\hat{i}},\ r_T^{\hat{i}} = r^{\hat{i}},\ \underline{\boldsymbol{\sigma}}^{\hat{i}} \le \bar{\rho}_e^{\hat{i}} \underline{\mathbf{1}},\ \underline{\boldsymbol{\varsigma}}^{\hat{i}} \le \bar{\rho}_r^{\hat{i}} \underline{\mathbf{1}},\ \kappa_T^{\hat{i}} \le \alpha^{\hat{i}} \text{ and } \pi_T^{\hat{i}} \le \xi^{\hat{i}} \alpha^{\hat{i}},$$

given the expected offers of seller $s^{\hat{i}}$'s competitors and the demand. The parameter $\xi^{\hat{i}}$ is the portion of the available capacity $\alpha^{\hat{i}}$ that can be provided as reserves. Seller $s^{\hat{i}}$ determines its offer $\Gamma^{\hat{i}}$ in two steps: first, $s^{\hat{i}}$ chooses feasible $e^{\hat{i}*}$ and $r^{\hat{i}*}$ so as to maximize expected profits, given ℓ_d, δ_d, p_d, $\alpha^{\hat{i}}$, $\xi^{\hat{i}}$, $\chi_e^{\hat{i}}(\cdot)$, $\bar{\rho}_e^{\hat{i}}$, $\rho_r^{\hat{i}}$ and the expected offers of seller $s^{\hat{i}}$'s competitors. Then, seller $s^{\hat{i}}$ constructs an offer $\Gamma^{\hat{i}*}$ to ensure the sale of $e^{\hat{i}*}$ and $r^{\hat{i}*}$ if the other competitors offer according to the information seller $s^{\hat{i}}$ has.

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6. This is done to avoid the modeling of the interaction between players. Equivalently, we may say that there are many strategic sellers but they determine their strategies assuming all other player's strategies are fixed.

We now characterize the feasible two-tuples $\left(e^{\hat{i}}, r^{\hat{i}}\right)$. Denoting the energy prices when $\Delta \underset{\sim}{L}_d = 0$ and $\Delta \underset{\sim}{L}_d = \delta_d$ as a function of $e^{\hat{i}}$ and $r^{\hat{i}}$ by $\lambda_e^{\hat{i}0}\left(e^{\hat{i}}, r^{\hat{i}}\right)$ and $\lambda_e^{\hat{i}\delta}\left(e^{\hat{i}}, r^{\hat{i}}\right)$, respectively, and the reserves price function by $\lambda_r^{\hat{i}}(\cdot,\cdot)$, we have the following result:

Theorem 2.1: *The two-tuple* $\left(e^{\hat{i}}, r^{\hat{i}}\right)$ *is feasible if and only if*

$$r^{\hat{i}}\left[\lambda_e^{\hat{i}0}\left(e^{\hat{i}}, r^{\hat{i}}\right) - \overline{\rho}_e^{\hat{i}}\right] \leq r^{\hat{i}} \lambda_r^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right). \tag{2.22}$$

■

Proof: First we prove the necessary condition of feasibility. Consider a feasible pair $\left(e^{\hat{i}}, r^{\hat{i}}\right)$, with $r^{\hat{i}} > 0$ since for $r^{\hat{i}} = 0$ the equality (2.22) is trivial. Suppose seller $s^{\hat{i}}$ offers $\kappa_T^{\hat{i}} = e^{\hat{i}} + r^{\hat{i}}$ MW in the market, and sells $e^{\hat{i}}$ MWh of energy. We show that because $r^{\hat{i}}$ MW are sold as reserves (from the feasibility assumption), (2.22) is satisfied.

The increment in social welfare when the ISO buys one extra MWh/h from the offer block $\Gamma_j^{\hat{i}k} = \left\{\sigma_j^{\hat{i}k}, \varsigma_j^{\hat{i}k}, \kappa_j^{\hat{i}k}, \pi_j^{\hat{i}k}\right\}$ of generator *j* of seller $s^{\hat{i}}$ instead of buying it from the most expensive block that sells energy is given by

$$\lambda_e^{\hat{i}0}\left(e^{\hat{i}}, r^{\hat{i}}\right) - \sigma_j^{\hat{i}k}. \tag{2.23}$$

Similarly, the increment in social welfare when the ISO buys one extra MW of reserves from the same offer block of generator *j* of seller $s^{\hat{i}}$, instead of buying it from the most expensive block that sells reserves, is given by

$$\lambda_r^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right) - \varsigma_j^{\hat{i}k}. \tag{2.24}$$

Whenever (2.23) or (2.24) is positive, the ISO would buy the corresponding service from seller $s^{\hat{i}}$ which results in positive savings. If both are positive, the ISO would buy the service that obtains the larger savings. Therefore, seller $s^{\hat{i}}$ sells reserves from offer block k of generator j whenever

$$max\left\{0, \lambda_e^{\hat{i}0}\left(e^{\hat{i}}, r^{\hat{i}}\right) - \sigma_j^{\hat{i}k}, \lambda_r^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right) - \varsigma_j^{\hat{i}k}\right\} = \lambda_r^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right) - \varsigma_j^{\hat{i}k}. \tag{2.25}$$

Expression (2.25) holds, since $s^{\hat{i}}$ sells reserves. Thus,

$$\lambda_e^{\hat{i}0}\left(e^{\hat{i}}, r^{\hat{i}}\right) - \sigma_j^{\hat{i}k} \leq \lambda_r^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right) - \varsigma_j^{\hat{i}k}, \tag{2.26}$$

Since $\sigma_j^{\hat{i}k} \leq \overline{\rho}_e^{\hat{i}}$ and $\varsigma_j^{\hat{i}k} \geq 0$,

$$\lambda_e^{\hat{i}0}\left(e^{\hat{i}}, r^{\hat{i}}\right) - \overline{\rho}_e^{\hat{i}} \leq \lambda_r^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right), \tag{2.27}$$

and so (2.22) holds.

Now we prove the sufficiency condition. Without loss of generality and for notational simplicity, we assume that the capacity of the generator j of seller $s^{\hat{i}}$ is larger than $e^{\hat{i}} + r^{\hat{i}}$, so that we only need to consider the offer blocks for generator j of seller $s^{\hat{i}}$. Assume $r^{\hat{i}} > 0$. We propose the following offer made of two blocks: for the first block,

$$\sigma_j^{\hat{i}1} = 0,\ \varsigma_j^{\hat{i}1} = \overline{\rho}_r^{\hat{i}},\ \kappa_j^{\hat{i}1} = e^{\hat{i}},\ \pi_j^{\hat{i}1} = 0, \tag{2.28}$$

and for the second block,

$$\sigma_j^{\hat{i}2} = \overline{\rho}_e^{\hat{i}},\ \varsigma_j^{\hat{i}2} = 0,\ \kappa_j^{\hat{i}2} = \pi_j^{\hat{i}2} = r^{\hat{i}}. \tag{2.29}$$

By inspection, both blocks fulfill the mitigation requirement $\sigma_j^{\hat{i}k} \leq \overline{\rho}_e^{\hat{i}},\ \varsigma_j^{\hat{i}k} \leq \overline{\rho}_r^{\hat{i}},\ k = 1,2$. We will show that if (2.22) holds, then the proposed offer is successful and

$$e_T^{\hat{i}} = e^{\hat{i}}, \tag{2.30}$$

$$r_T^{\hat{i}} = r^{\hat{i}}. \tag{2.31}$$

Replacing (2.28) and (2.29) in (2.24) and (2.26), by the previous argument block 2 sells reserves if

$$max\left\{0, \lambda_e^{\hat{i}0}\left(e^{\hat{i}}, r^{\hat{i}}\right) - \overline{\rho}_e^{\hat{i}}, \lambda_r^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right)\right\} = \lambda_r^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right). \tag{2.32}$$

Clearly,

$$\lambda_r^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right) \geq 0, \tag{2.33}$$

since prices are nonnegative, and from (2.22),

$$\lambda_e^{\hat{i}0}\left(e^{\hat{i}}, r^{\hat{i}}\right) - \overline{\rho}_e^{\hat{i}} \leq \lambda_r^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right). \tag{2.34}$$

Therefore, (2.32) holds and block 2 sells $r^{\hat{i}}$ MW of reserves. If a block has $\pi_j^{\hat{i}k} = 0,$ it sells energy if (2.23) is positive. Then, the block 1 of the proposed offer sells energy if

$$\lambda_e^{\hat{i}0}\left(e^{\hat{i}}, r^{\hat{i}}\right) \geq 0, \tag{2.35}$$

which clearly holds. Then, block 1 of the proposed offer sells $e^{\hat{i}}$ MWh of energy, and so $\left(e^{\hat{i}}, r^{\hat{i}}\right)$ is feasible. The cases when $e^{\hat{i}}$ or $r^{\hat{i}}$ is zero are straightforward.

■

The determination of $e^{\hat{i}*}$ and $r^{\hat{i}*}$ is obtained from the solution of the following optimization problem:

$$
(SSP)\begin{cases} \max\limits_{e^{\hat{i}},r^{\hat{i}}} & \Pi_d^{\hat{i}}\left(e^{\hat{i}},r^{\hat{i}}\right) \\ & s.t. \\ & e^{\hat{i}}+r^{\hat{i}} \le \alpha^{\hat{i}} \\ & r^{\hat{i}} \le \xi^{\hat{i}} \alpha^{\hat{i}} \\ & e^{\hat{i}},r^{\hat{i}} \ge 0 \\ & r^{\hat{i}}\left[\lambda_e^{\hat{i}0}\left(e^{\hat{i}},r^{\hat{i}}\right)-\overline{\rho}_e^{\hat{i}}\right] \le r^{\hat{i}}\lambda_r^{\hat{i}}\left(e^{\hat{i}},r^{\hat{i}}\right) \end{cases} \tag{2.36}
$$

where

$$
\begin{aligned} \Pi_d^{\hat{i}}\left(e^{\hat{i}},r^{\hat{i}}\right) = & \, p_d\left(\lambda_e^{\hat{i}0}\left(e^{\hat{i}},r^{\hat{i}}\right)e^{\hat{i}}-\chi_e^{\hat{i}}\left(e^{\hat{i}}\right)+\lambda_r^{\hat{i}}\left(e^{\hat{i}},r^{\hat{i}}\right)r^{\hat{i}}-\chi_r^{\hat{i}}\left(r^{\hat{i}}\right)\right) \\ & +\left(1-p_d\right)\left(\lambda_e^{\hat{i}\delta}\left(e^{\hat{i}},r^{\hat{i}}\right)\left(e^{\hat{i}}+r^{\hat{i}}\right)-\chi_e^{\hat{i}}\left(e^{\hat{i}},r^{\hat{i}}\right)+\lambda_r^{\hat{i}}\left(e^{\hat{i}},r^{\hat{i}}\right)r^{\hat{i}}\right). \end{aligned} \tag{2.37}
$$

An algorithm for the construction of the offer once $\left(e^{\hat{i}*},r^{\hat{i}*}\right)$ is determined is provided in Appendix B. Note that the optimal two-tuple $\left(e^{\hat{i}*},r^{\hat{i}*}\right)$ explicitly takes into account the uncertainty in the demand. Note also that for cases requiring a more detailed multistate representation of the availability and demand r.v.'s, an extension of the (*SSP*) is straightforward.

2.5 Reliability Impacts of Seller Behavior

We next investigate the impacts of seller behavior on reliability. In a competitive environment, if the total amount offered in the CERM is at least as large as the demand, then all the demand is served. Hence, in the assessment of the impacts of seller behavior on reliability we analyze the capacity offered in the CERM. The total capacity offered by price taker s^i in the CERM is given by

$$
\kappa_T^i = \alpha^i, \tag{2.38}
$$

as a price taker offers all its available capacity. Thus, we conclude that the behavior of a price taker does not impact system reliability.

We now focus on the strategic seller behavior. The strategic model (2.36) provides the two-tuple $\left(e^{\hat{i}}, r^{\hat{i}}\right)$ of quantities to sell. Hence, we express $\kappa_T^{\hat{i}}$ in terms of $\left(e^{\hat{i}}, r^{\hat{i}}\right)$ to be able to compare $\kappa_T^{\hat{i}}$ with $\alpha^{\hat{i}}$. We consider three distinct cases which clearly cover the spectrum of interest:

(a) the amount of energy and reserves to sell is large enough so that the corresponding market clearing prices are smaller or equal to the offer price caps,

(b) the amount of energy to sell is small enough so that the market clearing price for energy is larger than the offer price cap for energy, and

(c) the amount of reserves to sell is small enough so that the market clearing price for reserves is larger than the offer price cap for reserves.

The conditions characterizing these three cases are stated in Table 2.2. In case *(a)*, seller $s^{\hat{i}}$ can economically withhold capacity, while in cases *(b)* and *(c)* seller $s^{\hat{i}}$ cannot economically withhold since prices are higher than seller $s^{\hat{i}}$'s offer price caps. From the assumption that seller $s^{\hat{i}}$ prefers economic withholding to physical withholding, we obtain that in case *(a)* seller $s^{\hat{i}}$ offers all its available capacity, while in cases *(b)* and *(c)* seller $s^{\hat{i}}$ only offers the quantities seller $s^{\hat{i}}$ expects to sell. Therefore, in such cases seller $s^{\hat{i}}$ physically withholds capacity and the capacity $\kappa_T^{\hat{i}}$ offered by the strategic seller $s^{\hat{i}}$ in the CERM is characterized by

$$\kappa_T^{\hat{i}} < \alpha^{\hat{i}} . \tag{2.39}$$

Then, we have that

$$\kappa_T < \alpha . \tag{2.40}$$

Table 2.2: Offered capacity as a function of $\left(e^{\hat{i}}, r^{\hat{i}}\right)$

case	conditions	κ_T^{i}
(a)	$\lambda_e^{\hat{i}0}\left(e^{\hat{i}}, r^{\hat{i}}\right) \le \bar{\rho}_e^{\hat{i}}$ $\lambda_r^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right) \le \bar{\rho}_r^{\hat{i}}$	$\alpha^{\hat{i}}$
(b)	$\lambda_e^{\hat{i}0}\left(e^{\hat{i}}, r^{\hat{i}}\right) \ge \bar{\rho}_e^{\hat{i}}$	$e^{\hat{i}} + r^{\hat{i}}$
(c)	$\lambda_r^{\hat{i}}\left(e^{\hat{i}}, r^{\hat{i}}\right) \ge \bar{\rho}_r^{\hat{i}}$	$e^{\hat{i}} + r^{\hat{i}}$

If we do the analysis in the month prior to the hour *h*, when there are many uncertainties associated to the hour *h* available capacities, the equivalent to (2.40) is

$$P\left\{\underset{\sim}{K} < \underset{\sim}{A}\right\} > 0 , \tag{2.41}$$

where we denote the total offered capacity $\underset{\sim}{K}$ as an r.v. to explicitly show the uncertainty. That is, the probability of physical capacity withholding is positive. There is a loss of load event whenever

$$\underset{\sim}{K} < \underset{\sim}{L} \tag{2.42}$$

From (2.41) and (2.42), it follows that there may be a loss of load event even when there are sufficient available resources in the system, i.e.,

$$P\left\{\underset{\sim}{K} < \underset{\sim}{L} \le \underset{\sim}{A}\right\} \ge 0 . \tag{2.43}$$

The event in (2.43) is not captured by the metric values (2.12) - (2.15) and so they overstate the system reliability. Hence, there is a need for resource adequacy metrics that explicitly take into account market realities.

We propose to modify the expressions in (2.12) - (2.15) to explicitly represent the market outcomes. The basic modification is the replacement of $\underset{\sim}{A}$ by $\underset{\sim}{K}$. We denote the modified values with a superscript *M*. The *resource availability margin* $\underset{\sim}{R}^M$, *loss of load probability* $LOLP^M$*, expected unserved energy* $\mathscr{U}^M$ and *expected outage costs* $\mathscr{C}_o^M$ are given by

$$\underset{\sim}{R}^M = \frac{\underset{\sim}{K} - \underset{\sim}{L}}{\underset{\sim}{L}}, \tag{2.44}$$

$$LOLP^M = P\left\{\underset{\sim}{L} > \underset{\sim}{K}\right\}, \tag{2.45}$$

$$\mathscr{U}^M = H \cdot E\left\{\underset{\sim}{L} - \underset{\sim}{K} \,\middle|\, \underset{\sim}{L} > \underset{\sim}{K}\right\} LOLP^M, \tag{2.46}$$

and

$$\mathscr{C}_o^M = wH \cdot E\left\{\underset{\sim}{L} - \underset{\sim}{K} \,\middle|\, \underset{\sim}{L} > \underset{\sim}{K}\right\} LOLP^M. \tag{2.47}$$

Under the assumption that all offers submitted to the CERM are backed by available capacity, it is straightforward to show that

$$P\left\{\underset{\sim}{R}^M \leq \underset{\sim}{R}\right\} = 1,$$

$$LOLP^M \geq LOLP,$$

$$\mathscr{U}^M \geq \mathscr{U},$$

and

$$\mathcal{C}_o^M \geq \mathcal{C}_o .$$

We term $LOLP$, $\mathcal{U}$, and $\mathcal{C}_o$ as *limiting values* for $LOLP^M$, $\mathcal{U}^M$, and $\mathcal{C}_o^M$, respectively.

2.6 Resource Adequacy Program Incorporation

At this stage, we model the resource adequacy program as a black box with the distributions of $\underset{\sim}{K}$, $\underset{\sim}{L}$, and $\underset{\sim}{A}$ as inputs and the incentives as a function $\varphi^i(\cdot)$ of the capacity offered by each seller s^i in the CERM for hour h as the outputs. The function $\varphi^i(\cdot)$ is nondecreasing and can take positive or negative values. If $\varphi^i(\cdot)$ takes a negative value we interpret it as a disincentive. In the next chapter, we introduce the resource adequacy program design and the black box turns into a white box.

Seller s^i knows the incentive function $\varphi^i(\cdot)$ at the time of CERM offer preparation, and thus adds it to the profit function $\Pi_d^i(\cdot,\cdot)$ to be maximized to get a new objective function $\breve{\Pi}_d^i\left(e^i, r^i, \kappa_T^i\right)$,

$$\breve{\Pi}_d^i\left(e^i, r^i, \kappa_T^i\right) = \Pi_d^i\left(e^i, r^i\right) + \varphi^i\left(\kappa_T^i\right). \tag{2.48}$$

In determining its offers, a price taker computes the marginal incentive and subtracts it from its costs. Hence, if we update the factor ζ_j^{ik} so that it takes into account the marginal incentives, the model of the price taker does not change when incentives are provided. However, the model of the strategic seller may change when there are incentives for offering in the CERM. Using (2.36) and the results in Table 2.2, we express the strategic seller model as the three maximization problems

$$
(NW)\begin{cases}
\max\limits_{e^{\hat{i}},r^{\hat{i}}} & \breve{\Pi}_d^{\hat{i}}\left(e^{\hat{i}},r^{\hat{i}}\right)=\Pi_d^{\hat{i}}\left(e^{\hat{i}},r^{\hat{i}}\right)+\varphi^{\hat{i}}\left(\alpha^{\hat{i}}\right)\\
s.t. & \\
 & \left(e^{\hat{i}},r^{\hat{i}}\right)\in \mathbb{F}^{\hat{i}}\\
 & \lambda_e^{\hat{i}0}\left(e^{\hat{i}},r^{\hat{i}}\right)\le \bar{\rho}_e^{\hat{i}}\\
 & \lambda_r^{\hat{i}}\left(e^{\hat{i}},r^{\hat{i}}\right)\le \bar{\rho}_r^{\hat{i}}
\end{cases} \tag{2.49}
$$

$$
(WE)\begin{cases}
\max\limits_{e^{\hat{i}},r^{\hat{i}}} & \breve{\Pi}_d^{\hat{i}}\left(e^{\hat{i}},r^{\hat{i}}\right)=\Pi_d^{\hat{i}}\left(e^{\hat{i}},r^{\hat{i}}\right)+\varphi^{\hat{i}}\left(e^{\hat{i}}+r^{\hat{i}}\right)\\
s.t. & \\
 & \left(e^{\hat{i}},r^{\hat{i}}\right)\in \mathbb{F}^{\hat{i}}\\
 & \lambda_e^{\hat{i}0}\left(e^{\hat{i}},r^{\hat{i}}\right)\ge \bar{\rho}_e^{\hat{i}}
\end{cases} \tag{2.50}
$$

$$
(WR)\begin{cases}
\max\limits_{e^{\hat{i}},r^{\hat{i}}} & \breve{\Pi}_d^{\hat{i}}\left(e^{\hat{i}},r^{\hat{i}}\right)=\Pi_d^{\hat{i}}\left(e^{\hat{i}},r^{\hat{i}}\right)+\varphi^{\hat{i}}\left(e^{\hat{i}}+r^{\hat{i}}\right)\\
s.t. & \\
 & \left(e^{\hat{i}},r^{\hat{i}}\right)\in \mathbb{F}^{\hat{i}}\\
 & \lambda_r^{\hat{i}}\left(e^{\hat{i}},r^{\hat{i}}\right)\ge \bar{\rho}_r^{\hat{i}}
\end{cases} \tag{2.51}
$$

where $\mathbb{F}^{\hat{i}}$ is the set of solutions that satisfy the constraints in (2.36). Seller $s^{\hat{i}}$ chooses the result of the optimization problem in (2.49) - (2.51) that yields the highest expected profits.

In a competitive environment, all demand is served whenever the total amount offered in the CERM is at least as large as the demand. The amounts to offer result from the solution of (2.49) - (2.51), and so the distribution of $\underset{\sim}{K}$ is obtained using the model (2.49) - (2.51). The distribution of $\underset{\sim}{K}$ is a result of market economics. Moreover, the distribution of $\underset{\sim}{K}$, together with that of $\underset{\sim}{L}$, characterizes the system reliability. Therefore, the model (2.49) - (2.51) provides an explicit linkage between reliability and economics.

In this chapter, we presented the analytical basis for reliability evaluation in a market environment. In next chapter we present the proposed design for a resource adequacy program and we analyze it using the models introduced in this chapter.

CHAPTER 3

PROGRAM DESIGN

In this chapter, we present the proposed design for a short-term resource adequacy program and its analysis. The basic premise of the design is a "carrots and sticks" approach where a participating generation firm receives incentives to make a commitment to behave in such a way so as to improve system reliability, but is also penalized whenever it fails to comply with its commitment. In the analysis of the design, we provide sufficient conditions for ensuring reliability improvement results. The proposed design and analysis constitute a major contribution of this thesis.

The chapter contains three sections. In Section 3.1, we introduce the program design and outline its key components. We follow this with our analytical assessment of the characteristics and impacts of the design in Section 3.2. In Section 3.3, we provide a simple implementation of the design.

3.1 The Proposed Design

We design the short-term resource adequacy program to meet the goals delineated in Chapter 1 for such programs. Our proposed design provides:

- a direct link between reliability and market economics;
- incentives to discourage the exercise of physical capacity withholding by generation entities; and
- explicit penalties for noncompliance with commitments made.

As part of our design philosophy, we give selling entities explicit incentives for desired behavior and explicit disincentives for undesired behavior. In addition, we provide selling entities as much flexibility as possible.

The proposed program is based on the implementation of the capacity requirements described in Section 1.2. To attain the desired resource adequacy level, we use the capacity requirements imposed on the LSEs. These requirements are translated into *capacity credits requirements* that are obligated to be met on a month-ahead basis. We allow the requirements to be price-dependent[1] to explicitly link reliability and economics. We use a single buyer for capacity credits, and that is the ISO. The single buyer must purchase a quantity of capacity credits to meet the total LSE price-dependent capacity credits requirements at the purchase price. The single buyer then passes on the costs of capacity credits to the LSEs.[2] As the compliance of the LSEs with the capacity credits requirements is guaranteed by the single buyer, no penalties are needed on the LSEs to enforce the purchase of the capacity credits required.

The suppliers of capacity credits are firms that are *physically* capable to deliver energy and power. The participation of these firms in the resource adequacy program is voluntary. Each seller of capacity credits is obligated to submit offers in the CERM for each hour of the month and to deliver the services committed to under the accepted offers. These conditions require the sellers to have the amount of committed generation capacity in the sale of the capacity credits. Note that this amount of capacity cannot be on planned maintenance.

---

1. Price-independent requirements become a special limiting case of price-dependent requirements.
2. Self-supplying LSEs are exempted. In the remainder of this report, we consider only LSEs which do not self-provide capacity credits.

We use *monthly capacity credits* contracts as the vehicle to meet the capacity credits requirements. Monthly capacity credits for a specified capacity c MW may be viewed as a set of contracts of one hour duration for a capacity c, with one contract for each hour. We refer to the one-hour contracts as *hourly capacity credits*. Once each month, there is a capacity credits market (CCM). The CCM is used by the ISO, in its role as the single buyer, for buying the total LSE monthly capacity credits from the selling entities. We propose to use a uniform-price double auction market mechanism for the CCM. The single buyer submits the demand curve to the CCM. This demand curve is determined by the price-dependent capacity credits requirements. The generation firms submit offers of monthly capacity credits to the CCM. These offers are sorted by increasing prices to construct the supply curve. The demand and supply curves are used to determine the total market clearing quantity, each individual seller's quantity, and the market clearing price for monthly capacity credits. The market clearing price is paid by the ISO to each seller of monthly capacity credits, and is paid by each LSE for its purchases.

We propose to allow the secondary trading of hourly capacity credits among firms *physically* capable to deliver energy and power.[3] Monthly capacity credits are not tied to particular units at the time of clearing the CCM. The actual generation units used to meet the sellers' obligations are determined by the sellers after the CERM for each hour h clears in the day-ahead. Moreover, due to the secondary markets, the capacity used to

3. The secondary trading of capacity credits provides extra flexibility to the capacity credits sellers, gives a way to avoid seller penalties when the capacity is unavailable, and stresses that the system needs the requisite amount of available capacity regardless of which generators provide it.

fulfill the obligation need not belong to the same firm that sold the capacity credits in the CCM.[4]

Whenever a seller of capacity credits fails to comply with its obligation for any hour of the month, a penalty is imposed for each such hour independent of the reasons for noncompliance and notwithstanding any prior notification of the ISO. The objective of the penalty mechanism is to drive the sellers in the program to compliance. Hence, the dollar amounts of the penalties need to be "sufficiently large" so as to *encourage* the compliance of the selling firms participating in the resource adequacy program, but not "exceedingly large" to *discourage* the participation of generation firms in the CCM.

We next discuss the rationale for the proposed design. Generation firms are assumed to be rational entities, and the CCM provides an opportunity for them to increase revenues, and consequently their profits. Thus, generation firms have incentives to participate in the CCM. Each firm whose submitted offers to the CCM are accepted, gets to sell capacity credits and receives the payments for each MW provided. Capacity credits sellers are penalized whenever they fail to meet their commitments by failure to participate in the CERM, i.e., capacity withholding. Consequently, capacity credits sellers have disincentives to withhold capacity. This is in contrast to those generation firms which do not sell capacity credits either due to failure to participate in the CCM or for submitting offers above CCM clearing price. Therefore, the proposed program provides an appropriate incentive/disincentive mechanism to generation firms so as not to physically withhold capacity from the CERM.

---

4. However, no double counting of capacity is allowed. That is, each MW of generation capacity can be used to meet the obligation of only 1 MW of capacity credits, regardless of which firm owns the generation capacity and which firm sold the capacity credit.

The main conceptual difference between the proposed program and the schemes described in Section 1.2 is that in the latter, firms sell "expected" available capacity from specific units. In contrast, in the proposed program, a seller of monthly capacity credits is selling a commitment to have actual available capacity for each hour of the month.

We conclude the design description by providing the time line in Figure 3.1. On a month-ahead basis, the monthly CCM takes place. Between the CCM and the CERM, generation firms are allowed to engage in capacity credits trades among themselves. At the specified hour h, there are balancing mechanisms to cover demand/supply variations. We point out that before the CERM outcomes are determined, all markets are financial. This means, in particular, that capacity credits are not linked to the actual physical units. Once the CERM clears, the outcomes have physical attributes since the specific accepted offers of energy and reserves are associated with particular physical units.

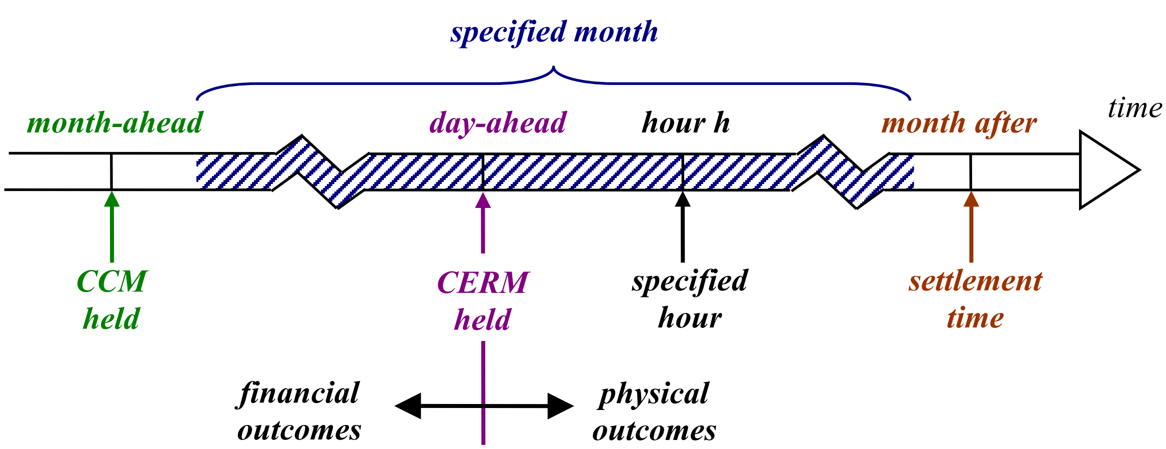


Figure 3.1: Time line in the proposed design.

3.2 Analysis of the Proposed Design

In this section, we analyze the impacts on reliability of the proposed design. We start by introducing some notation. We denote the integral of the seller s^i's marginal offer price in the CCM by $\vartheta^i\left(c^i\right)$, where c^i is the amount of monthly capacity credits sold by seller s^i. The function $\vartheta^i(\cdot)$ is defined over $\left[0,\xi^i\right]$, where ξ^i is the amount of capacity credits offered in the CCM by seller s^i with

$$\xi^i \leq g^i. \tag{3.1}$$

The vector of capacity credits offered quantities is denoted by $\underline{\boldsymbol{\xi}} \triangleq \left[\xi^1,\xi^2,...,\xi^S\right]'$ and the vector of quantities sold by $\underline{\boldsymbol{c}} \triangleq \left[c^1,c^2,...,c^S\right]'$.

The demand side in the CCM is characterized by the capacity credits demand curve $\phi\,(\cdot)$ submitted by the single buyer. The total capacity credits purchased by the single buyer is c_b. The objective of the CCM is the maximization of the *CCM social welfare* $\mathscr{S}_c(\cdot,\cdot)$, which is determined by Equation (3.2),

$$\mathscr{S}_c\left(\underline{\boldsymbol{c}},c_b\right) \triangleq \int_0^{c_b} \phi(y)\,dy - \sum_{i=1}^{S} \vartheta^i\left(c^i\right). \tag{3.2}$$

The outcomes $\left(\underline{\boldsymbol{c}},c_b\right)$ of the CCM must satisfy the supply-demand balance for capacity credits. Consequently, the CCM involves the solution of the following optimization problem:

$$(CCM)\begin{cases} \max\limits_{\underline{\boldsymbol{c}},\,c_b} \ \mathscr{S}\left(\underline{\boldsymbol{c}},c_b\right) \\ s.t. \\ \qquad \underline{\mathbf{1}}'\,\underline{\boldsymbol{c}} = c_b \leftrightarrow \ \rho_c \\ \qquad \quad \underline{\boldsymbol{c}} \leq \underline{\boldsymbol{\xi}} \\ \qquad \underline{\boldsymbol{c}},c_b \geq 0 \qquad \qquad . \end{cases} \tag{3.3}$$

The optimal solution $\left(\underline{\boldsymbol{c}}^*, c_b^*\right)$ of (3.3) determines the sales and purchases in the CCM. The capacity credits payments $\mathscr{P}_c$ made by the single buyer are then

$$\mathscr{P}_c = \rho_c^* c_b^*, \tag{3.4}$$

where ρ_c^* is the value of the dual variable corresponding to the monthly capacity credits constraint at the optimum.

In the analysis, we make use of the *shortage* r.v. $\underset{\sim}{S}$ and the *market-based shortage* r.v. $\underset{\sim}{S}^M$. These r.v.'s are defined in terms of the load r.v. $\underset{\sim}{L}$, the total available capacity r.v. $\underset{\sim}{A}$, and the total offered capacity in the CERM r.v. $\underset{\sim}{K}$ with

$$\underset{\sim}{S} \triangleq \underset{\sim}{L} - \underset{\sim}{A} \tag{3.5}$$

and

$$\underset{\sim}{S}^M \triangleq \underset{\sim}{L} - \underset{\sim}{K}. \tag{3.6}$$

Throughout this chapter we use the assumption introduced in Section 2.1 that the offers are backed by deliverable physical capacity. In other words, the total offered capacity $\underset{\sim}{K}$ and the total available capacity $\underset{\sim}{A}$ have the relationship

$$\boldsymbol{P}\left\{\underset{\sim}{K} \le \underset{\sim}{A}\right\} = 1. \tag{3.7}$$

We introduce the notion of *perfect compliance* in the program. Perfect compliance means that the generation firms meet their commitments to the physical extent possible. In the definition of perfect compliance we need to consider two nonoverlapping cases:

- the available capacity exceeds c_b: in this case, the total capacity offered in the CERM is at least as large as c_b;

- the available capacity is less than or equal to c_b: in such case, there is no physical withholding since all the available capacity is offered in the CERM.

Mathematically, we state:

Definition 3.1: *Perfect compliance in the resource adequacy program occurs if and only if*

$$\boldsymbol{P}\left\{\underset{\sim}{K} = \underset{\sim}{A} \middle| \underset{\sim}{A} \leq c_b\right\} = 1, \tag{3.8}$$

and

$$\boldsymbol{P}\left\{c_b \leq \underset{\sim}{K} \leq \underset{\sim}{A} \middle| \underset{\sim}{A} > c_b\right\} = 1. \tag{3.9}$$

■

To provide a basis for evaluating the impacts of the proposed design, we compare the reliability with and without the proposed program. Let $\underset{\sim}{K}_0$ and $\underset{\sim}{S}_0^M$ be the offered capacity in the CERM and the market-based shortage, respectively, without a resource adequacy program with

$$\underset{\sim}{S}_0^M = \underset{\sim}{L} - \underset{\sim}{K}_0. \tag{3.10}$$

Let $\underset{\sim}{K}$ and $\underset{\sim}{S}^M$ be the offered capacity in the CERM and the market-based shortage, respectively, with the proposed program. Then,

$$\underset{\sim}{S}^M = \underset{\sim}{L} - \underset{\sim}{K}. \tag{3.11}$$

To evaluate the reliability with and without the proposed program, we compare the results in terms of the r.v.'s $\underset{\sim}{S}_0^M$ and $\underset{\sim}{S}^M$.

We use the following lemma to show that the shortage $\underset{\sim}{S}^M$ with the proposed design is smaller than the shortage $\underset{\sim}{S}_0^M$ without a resource adequacy program:

Lemma: *Let c^i and κ_T^i be the capacity credits provided and the capacity offered in the CERM by seller s^i, respectively. Consider the situation in which the seller s^i provides $\tilde{c}^i$ capacity credits, with $\tilde{c}^i \geq c^i$. Then, the capacity $\tilde{\kappa}_T^i$ offered in the CERM cannot decrease, i.e.,*

$$\tilde{\kappa}_T^i \geq \kappa_T^i .$$

■

This lemma states that any increase in the amount of capacity credits physically provided by firm s^i cannot reduce the capacity offered in the CERM by that firm. The result in this lemma follows from the presence of the penalty scheme. The proof follows in a straightforward way by contradiction and is omitted. We use this lemma to obtain

Theorem 3.1*: The proposed program results in the shortage $\underset{\sim}{S}^M \leq \underset{\sim}{S}_0^M$, the shortage with no resource adequacy program.*

■

Proof: Without a resource adequacy program, each firm s^i sells zero capacity credits, i.e., $c^i = 0$. The implementation of the proposed program results in each firm s^i selling a nonnegative quantity of capacity credits, i.e., $\tilde{c}^i \geq c^i = 0$. The lemma ensures that $\tilde{\kappa}_T^i \geq \kappa_T^i$ and so

$$\tilde{\kappa}_T = \sum_i \tilde{\kappa}_T^i \geq \sum_i \kappa_T^i = \kappa_T . \tag{3.12}$$

Note that (3.12) is independent of the load r.v. $\underset{\sim}{L}$. Since

$$\boldsymbol{P}\left\{ \underset{\sim}{K} \geq \underset{\sim}{K}_0 \right\} = 1 , \tag{3.13}$$

we obtain

$$\boldsymbol{P}\left\{\underset{\sim}{S}^{M} \leq \underset{\sim}{S}_{0}^{M}\right\}=1. \tag{3.14}$$

Therefore, the shortage magnitude $\underset{\sim}{S}^{M}$ with the proposed program is less than $\underset{\sim}{S}_{0}^{M}$ without a program.

■

Let $\Psi\left(c^{i},\kappa_{T}^{i}\right)$ be the penalty imposed on seller s^{i} committed to providing c^{i} MW of capacity credits and offering κ_{T}^{i} MW in the CERM. The penalty $\Psi\left(\cdot,\cdot\right)$ is a monotonically nondecreasing function of the difference $c^{i}-\kappa_{T}^{i}$. Price takers do not physically withhold capacity, and so their behavior in the CERM is independent of the proposed program. The implementation of the proposed program therefore only impacts the strategic seller's behavior, and so we restrict our analysis to the impacts of the program implementation on the strategic seller $s^{\hat{i}}$'s behavior.[5] The profits in the CERM for providing $e^{\hat{i}}$ MWh of energy and $r^{\hat{i}}$ MW of reserves together with the impacts of the CCM commitment are

$$\breve{\Pi}_{d}^{\hat{i}}\left(e^{\hat{i}},r^{\hat{i}},\kappa_{T}^{\hat{i}},c^{\hat{i}}\right)\triangleq \Pi_{d}^{\hat{i}}\left(e^{\hat{i}},r^{\hat{i}}\right)-\Psi\left(c^{\hat{i}},\kappa_{T}^{\hat{i}}\right). \tag{3.15}$$

We analyze the impacts of a change $\Delta c^{\hat{i}}>0$ in the capacity credits provided by seller $s^{\hat{i}}$. We recall from Section 2.6 that the optimal solution of the strategic seller problem (SSP) is the solution of either (2.49), (2.50), or (2.51). When the optimal solution of (SSP) is the solution of either (2.50) or (2.51), the strategic seller $s^{\hat{i}}$ cannot

5. We assume there is only one strategic seller, denoted seller $s^{\hat{i}}$. Equivalently, we may say that there are many strategic sellers but they determine their strategies assuming all other players' strategies are fixed.

economically withhold, and so the offered capacity in the CERM changes by an amount $\Delta\kappa_T^{\hat{i}}$.[6] The Lemma implies that $\Delta\kappa_T^{\hat{i}} \geq 0$, and thus the change in the capacity credits provided shifts the CERM supply curves to the right, resulting in improving the market-based reliability and lowering the market clearing price.

We next consider the impacts of an increase in the penalty value. We assume the penalty function $\Psi(\cdot,\cdot)$ is a monotonically increasing function of a penalty coefficient v, and so we consider a change $\Delta v > 0$ in the penalty coefficient. Such a change results in similar impacts on the sellers' behavior as a change $\Delta c^{\hat{i}}$ in capacity credits. When the optimal solution of (SSP) is that of (2.50) or (2.51), the strategic seller cannot economically withhold, and so the strategic seller increases its capacity offered in the CERM, resulting in $\Delta\kappa_T^{\hat{i}} \geq 0$. Otherwise, the change in the penalty function has no impacts in the CERM.

The decrease in the shortage $\underset{\sim}{S}^M$ from the shortage $\underset{\sim}{S}_0^M$ corresponds to a reliability improvement. We term the improvement *positive* if there exist one or more loss of load conditions which are attenuated by the program. Formally, we have

Definition 3.2: *The proposed program improves reliability if and only if*

$$\boldsymbol{P}\left\{\underset{\sim}{S}^M \leq \underset{\sim}{S}_0^M\right\} = 1 . \tag{3.16}$$

The proposed program produces a positive improvement of reliability if

$$\boldsymbol{P}\left\{\left\{\underset{\sim}{S}^M < \underset{\sim}{S}_0^M\right\} \cap \left\{\underset{\sim}{S}_0^M > 0\right\}\right\} > 0 . \tag{3.17}$$

---

6. When the optimal solution of (SSP) is given by the solution of (2.49), economic withholding is possible and so an increase in the capacity credits provided by seller $s^{\hat{i}}$ may have no impacts in κ_T.

$\blacksquare$

Condition (3.17) means that there exists a loss of load condition, corresponding to a positive shortage $\underset{\sim}{S}_0^M > 0$, such that the program results in a positive change leading to $\underset{\sim}{S}^M < \underset{\sim}{S}_0^M$. In terms of Definition 3.2, we restate Theorem 3.1 as

Theorem 3.1*: The proposed program improves reliability.*

$\blacksquare$

There are certain analytical conditions that ensure positive reliability improvements. These are based on the perfect compliance of the sellers, the existence of loss of load conditions which are magnified by the exercise of physical withholding, and the purchase of a *sufficient quantity* of capacity credits by the ISO.

Theorem 3.2*: Under perfect compliance, with the CERM available capacity* $\underset{\sim}{K}_0$ *satisfying either*

$$\boldsymbol{P}\left\{\left\{\underset{\sim}{K}_0 < \underset{\sim}{L}\right\} \cap \left\{\underset{\sim}{K}_0 < c_b \leq \underset{\sim}{A}\right\}\right\} > 0 \tag{3.18}$$

or

$$\boldsymbol{P}\left\{\left\{\underset{\sim}{K}_0 < \underset{\sim}{L}\right\} \cap \left\{\underset{\sim}{K}_0 < \underset{\sim}{A} < c_b\right\}\right\} > 0\,, \tag{3.19}$$

the implementation of the proposed program results in a positive improvement in reliability.

$\blacksquare$

Proof: The definitions of $\underset{\sim}{S}^M$ in (3.11) and $\underset{\sim}{S}_0^M$ in (3.10) imply

$$\boldsymbol{P}\left\{\left\{\underset{\sim}{S}^M < \underset{\sim}{S}_0^M\right\} \cap \left\{\underset{\sim}{S}_0^M > 0\right\}\right\} = \boldsymbol{P}\left\{\left\{\underset{\sim}{K} > \underset{\sim}{K}_0\right\} \cap \left\{\underset{\sim}{K}_0 < \underset{\sim}{L}\right\}\right\}. \tag{3.20}$$

However, the event $\left\{\underset{\sim}{K} > \underset{\sim}{K}_0\right\}$ is the union of the mutually independent events

$$\begin{aligned}\left\{\underset{\sim}{K} > \underset{\sim}{K}_0\right\} = \left\{\underset{\sim}{K}_0 < c_b \le \underset{\sim}{K} \le \underset{\sim}{A}\right\} \cup \left\{\underset{\sim}{K}_0 < \underset{\sim}{K} = \underset{\sim}{A} < c_b\right\} \cup \\ \left\{\left\{\underset{\sim}{K}_0 < c_b \le \underset{\sim}{K} \le \underset{\sim}{A}\right\} \cup \left\{\underset{\sim}{K}_0 < \underset{\sim}{K} = \underset{\sim}{A} < c_b\right\}\right\}^C \cap \left\{\underset{\sim}{K} > \underset{\sim}{K}_0\right\},\end{aligned}$$

where the superscript C denotes the complement. Then,

$$\begin{aligned}\boldsymbol{P}\left\{\left\{\underset{\sim}{S}^M < \underset{\sim}{S}_0^M\right\} \cap \left\{\underset{\sim}{S}_0^M > 0\right\}\right\} \ge \boldsymbol{P}\left\{\left\{\underset{\sim}{K}_0 < c_b \le \underset{\sim}{K} \le \underset{\sim}{A}\right\} \cap \left\{\underset{\sim}{K}_0 < \underset{\sim}{L}\right\}\right\} + \\ \boldsymbol{P}\left\{\left\{\underset{\sim}{K}_0 < \underset{\sim}{K} = \underset{\sim}{A} < c_b\right\} \cap \left\{\underset{\sim}{K}_0 < \underset{\sim}{L}\right\}\right\}.\end{aligned} \tag{3.21}$$

Perfect compliance and the satisfaction of either (3.18) or (3.19) imply that

$$\begin{aligned}\boldsymbol{P}\left\{\left\{\underset{\sim}{S}^M < \underset{\sim}{S}_0^M\right\} \cap \left\{\underset{\sim}{S}_0^M > 0\right\}\right\} &= \boldsymbol{P}\left\{\left\{\underset{\sim}{K}_0 < \underset{\sim}{K}\right\} \cap \left\{\underset{\sim}{K}_0 < \underset{\sim}{L}\right\}\right\} \\ &\ge \boldsymbol{P}\left\{\left\{\underset{\sim}{K}_0 < c_b \le \underset{\sim}{A}\right\} \cap \left\{\underset{\sim}{K}_0 < \underset{\sim}{L}\right\}\right\} + \\ &\quad \boldsymbol{P}\left\{\left\{\underset{\sim}{K}_0 < \underset{\sim}{A} < c_b\right\} \cap \left\{\underset{\sim}{K}_0 < \underset{\sim}{L}\right\}\right\} \\ &> 0.\end{aligned} \tag{3.22}$$

■

We observe that perfect compliance by itself cannot ensure positive reliability improvements. To ensure that a positive reliability improvement is attained, the reliability metric values without the program need to be strictly larger than the corresponding limiting values presented in Section 2.5, and the quantity of capacity credits bought needs to be *sufficient* to make a difference in the offering behavior of the players in the CERM. These are the conditions (3.18) and (3.19).

We measure reliability using $LOLP^M$, $\mathscr{U}^M$, and $\mathscr{C}_o^M$ discussed in Chapter 2. We recall that the *limiting* values of $LOLP^M$, $\mathscr{U}^M$, and $\mathscr{C}_o^M$ are $LOLP$, $\mathscr{U}$, and $\mathscr{C}_o$. We next quantify the loose term *sufficient quantity* of capacity credits using the following theorem.

Theorem 3.3: *Under perfect compliance,* $c_b = \ell^p$ *guarantees the limiting values of the reliability metrics.* ■

Proof: Let $\omega \ge 0$ and consider the distribution of the market-based shortage $\underset{\sim}{S}^M$. Then

$$\boldsymbol{P}\left\{\underset{\sim}{S}^M > \omega\right\} = \boldsymbol{P}\left\{\underset{\sim}{S}^M > \omega \middle| \underset{\sim}{A} \le c_b\right\} \boldsymbol{P}\left\{\underset{\sim}{A} \le c_b\right\} + \boldsymbol{P}\left\{\underset{\sim}{S}^M > \omega \middle| \underset{\sim}{A} > c_b\right\} \boldsymbol{P}\left\{\underset{\sim}{A} > c_b\right\} \tag{3.23}$$

$$\le \boldsymbol{P}\left\{\underset{\sim}{L} - \underset{\sim}{A} > \omega \middle| \underset{\sim}{A} \le c_b\right\} \boldsymbol{P}\left\{\underset{\sim}{A} \le c_b\right\} + \boldsymbol{P}\left\{\underset{\sim}{L} - c_b > \omega \middle| \underset{\sim}{A} > c_b\right\} \boldsymbol{P}\left\{\underset{\sim}{A} > c_b\right\}, \tag{3.24}$$

where we made use of the perfect compliance definition in (3.8) and (3.9). Using (3.7) and (3.5), we also have

$$\begin{aligned} \boldsymbol{P}\left\{\underset{\sim}{S}^M > \omega\right\} &= \boldsymbol{P}\left\{\underset{\sim}{L} - \underset{\sim}{K} > \omega\right\} \\ &\ge \boldsymbol{P}\left\{\underset{\sim}{L} - \underset{\sim}{A} > \omega\right\} \\ &= \boldsymbol{P}\left\{\underset{\sim}{S} > \omega\right\}. \end{aligned} \tag{3.25}$$

Therefore, we bound the distribution of the market-based shortage in terms of the distribution of the available capacity and the demand, without considering market outcomes.

Consider any $c_b \ge \ell^p$, then

$$\begin{aligned} \boldsymbol{P}\left\{\underset{\sim}{S}^M > \omega \middle| \underset{\sim}{A} > c_b\right\} &= \boldsymbol{P}\left\{\underset{\sim}{L} - \underset{\sim}{K} > \omega \middle| \underset{\sim}{A} > c_b\right\} \\ &\le \boldsymbol{P}\left\{\ell^p - \underset{\sim}{K} > \omega \middle| \underset{\sim}{A} > c_b\right\} \\ &\le \boldsymbol{P}\left\{c_b - \underset{\sim}{K} > \omega \middle| \underset{\sim}{A} > c_b\right\} \\ &= 0 \end{aligned} \tag{3.26}$$

since the sellers have perfect compliance. Thus the expression in (3.23) simplifies to

$$\begin{aligned} \boldsymbol{P}\left\{\underset{\sim}{S}^M > \omega\right\} &= \boldsymbol{P}\left\{\underset{\sim}{S}^M > \omega \middle| \underset{\sim}{A} \le c_b\right\} P\left\{\underset{\sim}{A} \le c_b\right\} \\ &= \boldsymbol{P}\left\{\underset{\sim}{L} - \underset{\sim}{K} > \omega \middle| \underset{\sim}{A} \le c_b\right\} P\left\{\underset{\sim}{A} \le c_b\right\} \\ &= \boldsymbol{P}\left\{\underset{\sim}{L} - \underset{\sim}{A} > \omega \middle| \underset{\sim}{A} \le c_b\right\} P\left\{\underset{\sim}{A} \le c_b\right\} \\ &= \boldsymbol{P}\left\{\left\{\underset{\sim}{L} - \underset{\sim}{A} > \omega\right\} \cap \left\{\underset{\sim}{A} \le c_b\right\}\right\} \\ &= \boldsymbol{P}\left\{\underset{\sim}{L} - \underset{\sim}{A} > \omega\right\} \\ &= \boldsymbol{P}\left\{\underset{\sim}{S} > \omega\right\}. \end{aligned}$$

Therefore, for any $c_b \geq \ell^p$, and in particular for $c_b = \ell^p$, the c.d.f. of the market-based shortage r.v. $\underset{\sim}{S}^M$ is equal to the c.d.f. of the shortage $\underset{\sim}{S}$ without considering the market, for values of shortage of interest, i.e., $\omega \geq 0$. Therefore,

$$LOLP^M = LOLP,$$

$$\mathscr{U}^M = \mathscr{U},$$

and

$$\mathscr{C}_o^M = \mathscr{C}_o.$$

Since this is true whenever $c_b \geq \ell^p$, it holds specifically for $c_b = \ell^p$. Therefore, $c_b = \ell^p$ guarantees the limiting values of $LOLP^M$, $\mathscr{U}^M$, and $\mathscr{C}_o^M$.

■

From Theorem 3.3 we conclude that $c_b = \ell^p$ is a *sufficient quantity* of capacity credits and that c_b need not be larger than ℓ^p under the condition of perfect compliance. Note that Theorem 3.3 provides sufficient conditions for attaining the limiting values of the reliability metrics; these conditions need not be necessary.

3.3 Implementation of the Proposed Design

In this section, we discuss a simple straightforward implementation of the proposed design. From a system reliability point of view, the design implementation is characterized by the price-dependent capacity credits requirements and the penalty scheme on capacity credits providers.[7] The price-dependent capacity credits requirements are equal to the CCM demand curve. The implementation presented in this section uses a piece-wise linear function for the demand curve, and a fixed penalty per MW.

The implementation uses the following function $\phi(\cdot)$ for the capacity credits demand curve:

$$\phi(c_b) = max\left\{c_b^{max} - c_b, 0\right\} \cdot m, \tag{3.27}$$

where $-m < 0$ is the slope of the capacity credits demand curve, c_b is the amount of capacity credits bought by the ISO, and c_b^{max} is the minimum demand with a zero bid price. The price bid for capacity credits above c_b^{max} is zero, and so the marginal benefit of any quantity of capacity credits above c_b^{max} is also zero. Thus, the parameter c_b^{max} may be interpreted as an estimate of the amount of capacity credits above which reliability does not improve. We use the following corollary of Theorem 3.3 in the determination of the c_b^{max} value:

> ***Corollary:*** *Under perfect compliance, additional purchases of capacity credits above the quantity ℓ^p cannot bring additional reliability improvements above those obtained for total credits of ℓ^p. Moreover, $c_b = \ell^p$ is the minimum value of the total credits which guarantees the limiting values of the reliability metrics.*

■

This corollary indicates that the marginal value of capacity credits exceeding ℓ^p is zero. Hence, in the demand function we set the bid function to zero for all values of capacity

7. The other implementation characteristics, such as the capacity credit costs allocation scheme, do not impact system reliability, and so are not considered in this report.

greater or equal to ℓ^{p}. Figure 3.2 shows the nature of the bid function for capacity credits for a piecewise linear case.

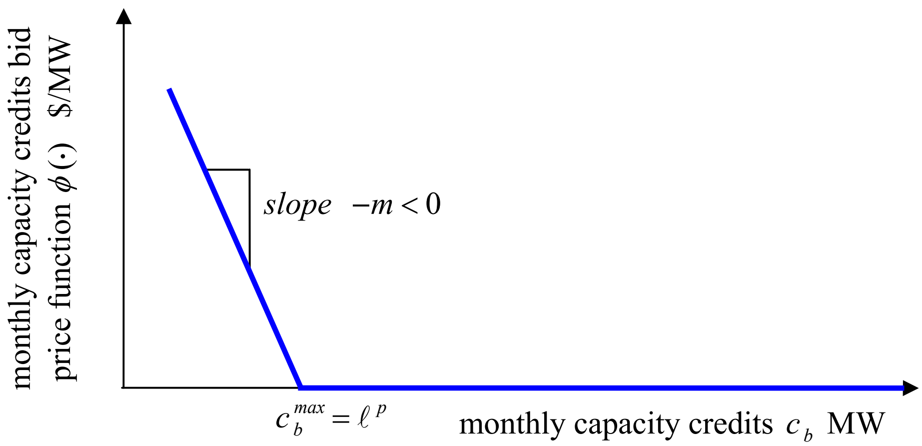


Figure 3.2: Proposed demand curve for monthly capacity credits.

With $\phi(\cdot)$ given by (3.27), the CCM social welfare $\mathscr{S}_c(\cdot,\cdot)$ is determined by

$$\mathscr{S}_c\left(\underline{\boldsymbol{c}}, c_b\right) = m\, c_b \left(c_b^{max} - \frac{c_b}{2} \right) - \sum_{i=1}^{S} \vartheta^{i}\left(c^{i}\right). \tag{3.28}$$

We use a simple fixed penalty value v \$/MW. For the penalty to be meaningful, the value of v must be strictly positive,[8] i.e., $v > 0$. Hence, the penalty function $\Psi(\cdot,\cdot)$ is given by

$$\Psi\left(c^{i}, \kappa_T^{i}\right) = max\left\{c^{i} - \kappa_T^{i}, 0\right\} \cdot v\,. \tag{3.29}$$

This simple penalty function has the advantage of being bounded. We illustrate in Figure 3.3 the penalties imposed on firm s^{i}, which provides c^{i} MW capacity credits, as a function of the capacity κ_T^{i} offered in the CERM. If seller s^{i} does not participate in the

8. A penalty value of zero means that effectively there is no program enforcement, and a negative penalty value would provide incentives for noncompliance.

CERM, it is assessed a penalty in the amount $\$ v c^i$, and if seller s^i offers at least c^i MW in the CERM, it is not penalized.

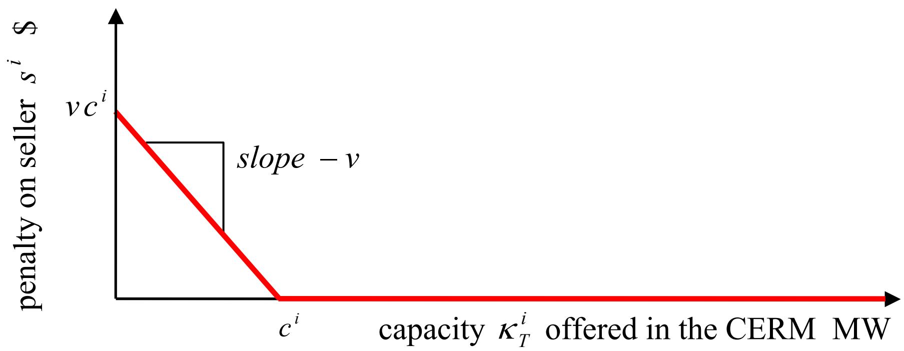


Figure 3.3: Penalty as a function of the capacity κ_T^i offered in the energy and reserves market.

The penalty coefficient given by

$$\bar{v} = \max_{1 \le i \le S} \left\{ g^i \left[\max \left\{ \bar{\rho}_e - \bar{\rho}_e^i, \bar{\rho}_r - \bar{\rho}_r^i \right\} \right] \right\} \tag{3.30}$$

guarantees perfect compliance. This can be shown using the fact that $\bar{v}$ is larger than or equal to the largest possible increase in profits a seller may obtain by physically withholding one MW from the CERM. However, setting $v = \bar{v}$ may be overly punitive. The penalty value has an impact on the payments $\mathscr{P}_c$ in the CCM since as penalties are raised, the payments $\mathscr{P}_c$ increase. Therefore, v needs to be "high enough" to provide disincentives for noncompliance but not so "high" as to render the resource adequacy program not cost effective. The value of v involves the trading-off between the capacity payments $\mathscr{P}_c$ and the reliability improvements due to the program implementation. We note that the relationship (3.30) between the penalty bound and the price caps implies that as $\bar{\rho}_e^i \to \bar{\rho}_e$ and $\bar{\rho}_r^i \to \bar{\rho}_r$, $\bar{v} \to 0$. In such a case, the bound $\bar{v}$ is small, and so a small value of v can guarantee perfect compliance.

In this chapter we have introduced a design for a short-term resource adequacy program. The proposed program provides a linkage between reliability improvements and the market economics since the system reliability depends on the capacity credits bought c_b and the penalty coefficient v. In addition, c_b is determined using the market-based mechanism given in (3.3). We use the program implementation described in this section to generate the simulation studies presented in next chapter.

CHAPTER 4

SIMULATION STUDIES

In this chapter, we summarize the results of simulation studies on three test systems to illustrate the performance of the proposed program. Each system has a distinct resource mix and a specified strategic seller market share. The results presented here are representative of the extensive simulation work performed and they serve to demonstrate that the proposed design implementation improves reliability in all systems tested.

This chapter contains four sections. In Section 4.1 we describe the nature of the simulation studies, we present the three test systems, and we give two reference cases with respect to which we do the performance quantification. Section 4.2 presents the assessment of impacts of the resource adequacy program. In Section 4.3 we study the variation of the impacts with respect to changes in the program's tuning parameters. Section 4.4 gives a summary of the results.

4.1 Nature of the Simulations

The objective of the studies on the various test systems is to assess the impacts of the proposed resource adequacy program on the system reliability in the period of interest. We use the cases with no resource adequacy program as benchmarks. We introduce the resource adequacy program and investigate the reliability metric values under the proposed program. In addition we report on the sensitivity studies for changes in the penalty coefficient, a bonus incentive, a change in the CCM demand curve slope, and the amount of capacity credits bought in the monthly CCM by the ISO. We use the simulation studies to determine the linkage between reliability and economics for the test systems, and to verify and illustrate the analytical results obtained in the previous chapter.

The three test systems are described in detail in Appendix D. We provide a summary of the test systems data in Table 4.1. Test systems A and B are small, and the main differences between them are the nature of the strategic seller capacity and the capacity margin. Test system C is a more realistic system with 100 generators and a strategic seller with a varied portfolio of generation resources. In each system, s^1 denotes the single strategic seller with each other seller in the system acting as a price taker.

Table 4.1: Test systems data

test system	A	B	C
number of generation firms	8	9	87
number of generators	10	12	100
peak demand (MW)	1650	3700	17800
capacity margin (%)	42.4	13.5	19.1
strategic seller capacity (MW)	750	600	2500
strategic seller market share (%)	32	14.3	11.8
strategic seller generation capacity type	base-load generation	peak-load generation	all

We use two different cases to serve as references for the analysis of the simulation results. The first is the case with no resource adequacy program. We refer to this case as the w-reference case. The second is the case with no resource adequacy program where physical withholding is not allowed, denoted as the n-reference case. The w-reference case serves to measure the reliability improvements when the program is implemented. The n-reference case serves to provide the upper bound for the reliability improvements attainable due to the implementation of the proposed program. The resource adequacy metrics for the n-reference case take the corresponding limiting values, since all the available capacity is offered in the CERM. We denote the w-reference case values of the metrics using a subscript *w*.

The reference case values of the metrics for the test systems are found in Table 4.2. All values of the metrics for the n-reference cases are strictly smaller than those for the w-reference cases, showing that the exercise of physical withholding hurts reliability in the test systems. We note that the impacts of the market outcomes on reliability for test system B are not as marked as those for test systems A and C. We attribute this phenomenon to the fact that the strategic seller in test system B is a firm selling peak loaded generation, whose benefits from physical withholding are considerably smaller than those of firms selling base loaded generation.

Table 4.2: Reference case metric values for the three test systems

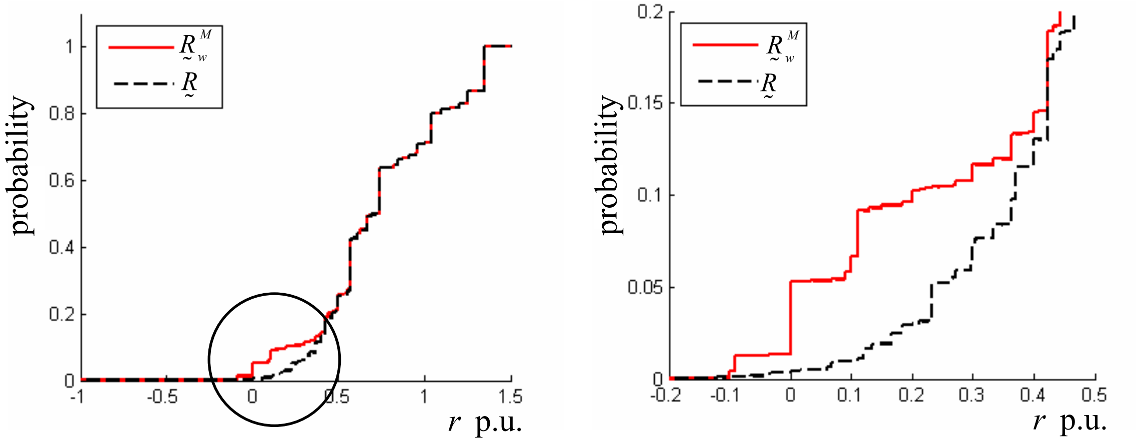
test system	A		B		C	
reference case	w	n	w	n	w	n
$LOLP^M$	$1.35\ 10^{-2}$	$0.34\ 10^{-2}$	$5.41\ 10^{-2}$	$4.14\ 10^{-2}$	$2.70\ 10^{-3}$	$0.07\ 10^{-3}$
$\mathscr{U}^M$ (MWh)	$1.48\ 10^{3}$	$0.31\ 10^{3}$	$1.18\ 10^{4}$	$0.92\ 10^{4}$	$3.67\ 10^{2}$	$0.14\ 10^{2}$
$\mathscr{C}_o^M$ (\$)	$0.15\ 10^{7}$	$0.03\ 10^{7}$	$0.12\ 10^{8}$	$0.09\ 10^{8}$	$0.37\ 10^{8}$	$0.01\ 10^{8}$
$\mathscr{C}_s$ (\$)	$5.81\ 10^{7}$	$4.48\ 10^{7}$	$1.22\ 10^{8}$	$1.08\ 10^{8}$	$3.20\ 10^{8}$	$1.10\ 10^{8}$
$\mathscr{C}_s + \mathscr{C}_o^M$ (\$)	$5.96\ 10^{7}$	$4.51\ 10^{7}$	$1.33\ 10^{8}$	$1.18\ 10^{8}$	$3.57\ 10^{8}$	$1.10\ 10^{8}$
$\mathscr{C}_o^M / \mathscr{C}_s$ (%)	2.5	0.7	9.8	8.5	11.6	0.0
$\mathscr{U}^M / \mathscr{E}$ (%)	0.15	0.03	0.53	0.41	0.00	0.00

The resource availability margin c.d.f. for the reference cases of test systems A, B, and C are shown in Figures 4.1 – 4.3. For each test system,

1. the distributions of $\underset{\sim}{R}_{w}^{M}$ and $\underset{\sim}{R}_{n}^{M} = \underset{\sim}{R}$ are identical for values of the resource availability margin less than -0.10;
2. the c.d.f. of $\underset{\sim}{R}_{w}^{M}$ is strictly larger than the c.d.f. of $\underset{\sim}{R}$ in the interval $\left[-0.02, 0\right]$ (Figure 4.1 (b), Figure 4.3 (b), and Figure 4.2 (b));
3. the most marked differences between the $\underset{\sim}{R}_{w}^{M}$ and $\underset{\sim}{R}$ distributions are for the resource availability margins with values in [0,0.2];
4. for large enough values of the margin, the distributions of $\underset{\sim}{R}_{w}^{M}$ and $\underset{\sim}{R}_{n}^{M} = \underset{\sim}{R}$ are identical.

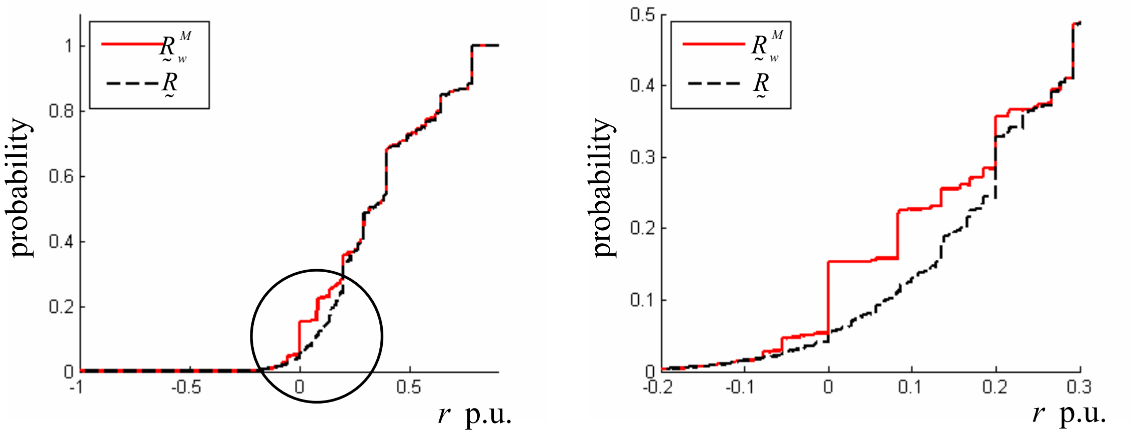
The second bullet means that the probability of a loss of load event is higher in the w-reference case than in the n-reference case, and so market-based reliability is strictly lower than the non-market-based reliability. In the cases characterized by the third bullet, the strategic seller has strong incentives to physically withhold capacity since the reserves are tight. Such actions result in the distinct differences between the two distributions. The first and fourth 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.

The differences in the reliability metrics for the two reference cases indicate that the reliability without the resource program is substantially lower than the attainable bounds. Consequently, there is room for reliability improvements by the implementation of the proposed resource adequacy program.



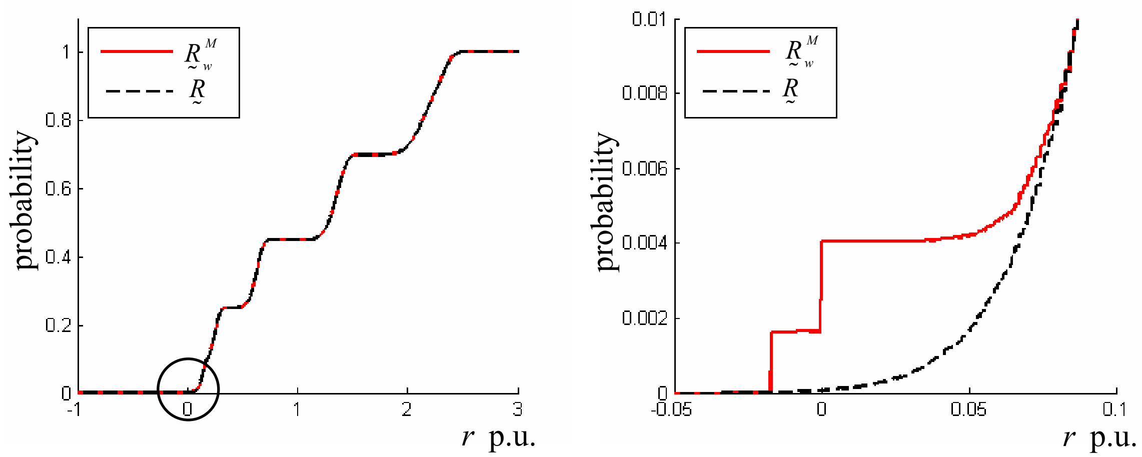
(a) ***(b)***

Figure 4.1: 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)*.



(a) ***(b)***

Figure 4.2: Resource availability margin c.d.f. for test system B in a range of values of practical interest, *(a)*; and a blowup of the circled region, *(b)*.



(a) ***(b)***

Figure 4.3: Resource availability margin c.d.f. for test system C in a range of values of practical interest, *(a)*; and a blowup of the circled region, *(b)*.

4.2 Evaluation of Impacts of the Resource Adequacy Program

We simulate the implementation of the resource adequacy program introduced in Section 3.3 in the test systems. The value of the program parameters used in the assessment are detailed in Table 4.3.

Table 4.3: Program parameters values

parameter	test system A	test system B	test system C
v \$/MW	10	30	20
m \$/MW^2	40	40	50
c_b^{max} MW	1650	3700	17800

We start by simulating the CCM. We explain this simulation using test system A. First we compute the capacity credits costs as indicated in Appendix C. Price taking firms offer all their capacity at marginal costs, and so the aggregated capacity credits supply curve for the price taking firms is equal to the aggregated capacity credits costs curve for the price taking firms; this curve is in Figure 4.4 (a). The capacity credits residual demand curve and the marginal costs of capacity credits for seller s^1 are in Figure 4.4 (b). We note the nonmonotonic nature of the marginal costs for the strategic seller. We assume seller s^1's offers are in block format with each block having 50 MW capacity. From Figure 4.4 (b) we conclude that the strategic seller s^1 does not have market power in the CCM, since the market clearing price does not depend on c^1 for $c^1 > 30$ MW, and seller s^1 does not gain from the price increment when selling $c^1 < 30$. Therefore, the monthly capacity credits price ρ_c^* is equal to 720 \$/MW and seller s^1 sells $c^{1*} = 500$

MW of capacity credits. The total amount of monthly capacity credits bought by the ISO is $c_b^* = 1632$ MW, and so the cost of the resource adequacy program is $\mathscr{P}_c = 1.17\ 10^6$ \$ per month, which is in the order of 2% of $\mathscr{C}_s$.

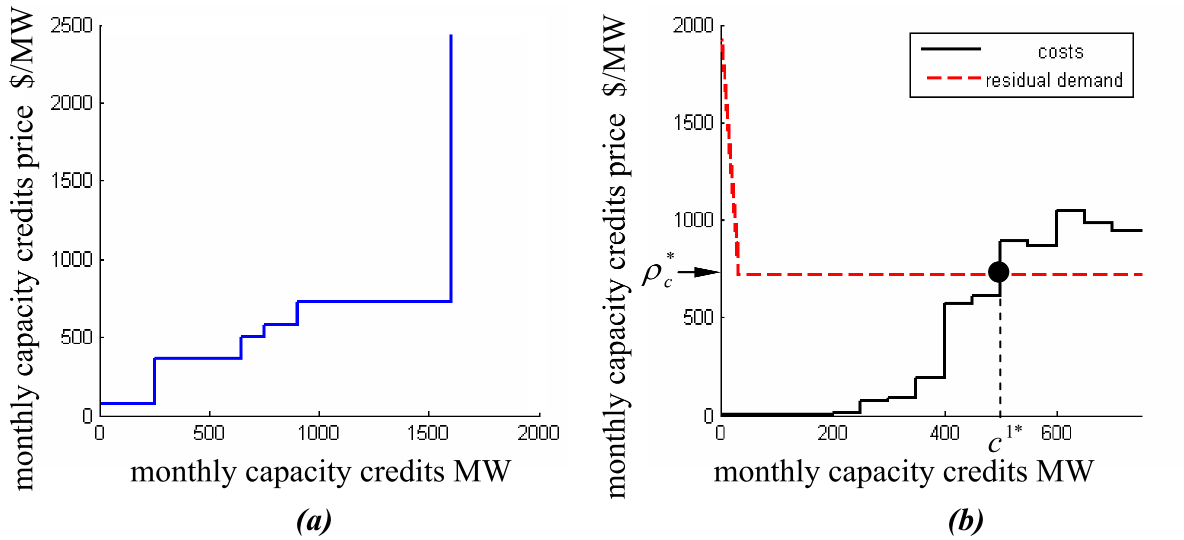


Figure 4.4: CCM simulation for test system A *(a)* aggregate supply curve of the price taking firms, and *(b)* residual demand and marginal costs for the strategic seller as a function of c^1 MW.

With the CCM results, we compute the reliability and market efficiency metric values using the models in Chapter 2. To do so, we condition on the state of the generation resources and the load. In systems A and B, all states were considered and so the results obtained are exact. For system C, since the number of states is very large, Monte Carlo simulation was used.[1] The resource adequacy metric values with the resource adequacy program implemented are presented in

Table **4.4**. The capacity credits prices in test systems B and C are higher than that of test system A due to the higher penalty coefficient.

1. We performed 200 000 iterations and obtained a standard error of 5.75% for $\mathscr{U}^M$, 30.15% for $\mathscr{U}$, 5.58% for $LOLP^M$, 23.03% for *LOLP*, and 0.19% for $\mathscr{C}_s$.

Table 4.4: Metric values when the program is implemented

test system	A	B	C
ρ_c^* (\$/MW)	0.72 10^3	1.94 10^3	1.44 10^3
c_b (MW)	1.63 10^3	3.65 10^3	1.78 10^4
$\mathscr{P}_c$ (\$)	1.17 10^6	7.10 10^6	2.56 10^7
$LOLP^M$	7.16 10^{-3}	4.93 10^{-2}	1.67 10^{-3}
$\mathscr{U}^M$ (MWh)	7.93 10^2	1.10 10^4	1.70 10^2
$\mathscr{C}_o^M$ (\$)	7.93 10^5	1.10 10^7	1.70 10^7
$\mathscr{C}_s$ (\$)	5.73 10^7	1.19 10^8	3.19 10^8
$\mathscr{C}_s + \mathscr{C}_o^M + \mathscr{P}_c$ (\$)	5.92 10^7	1.37 10^8	3.61 10^8
$\mathscr{P}_c / \mathscr{C}_s$ (%)	2.00	5.80	8.00

The reliability and market efficiency improvements when the proposed program is implemented are in Table 4.5. We note that reliability and market efficiency improve with respect to w-reference case in all test systems. However, the total system costs $\mathscr{C}_s + \mathscr{C}_o^M + \mathscr{P}_c$ may increase or decrease with the design implementation.

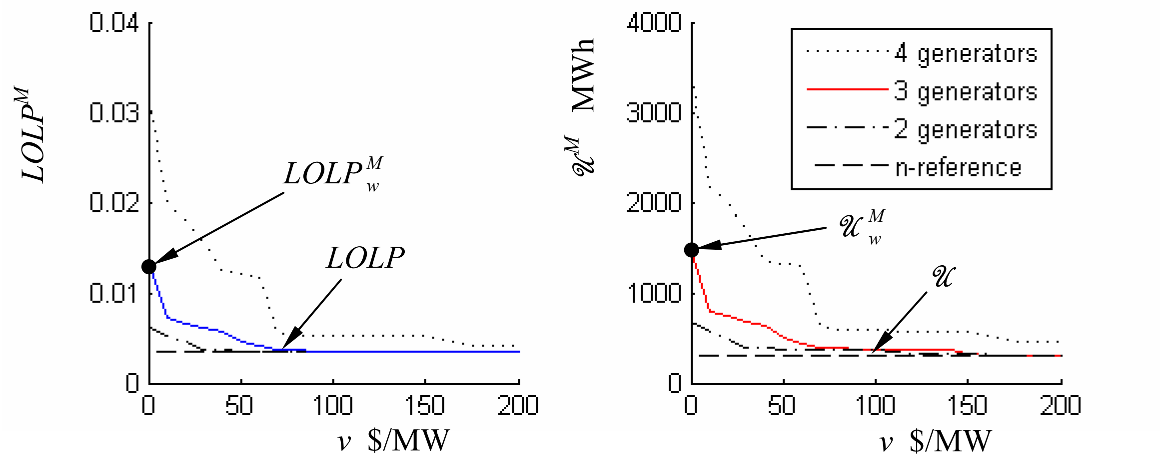
Table 4.5: Reliability and market efficiency improvements

test system	A	B	C
$LOLP^M$ (%)	46.9	8.9	53.4
$\mathscr{U}^M$ (%)	46.1	6.6	72.9
$\mathscr{C}_s$ (%)	1.3	2.4	0.3
$\mathscr{C}_s + \mathscr{C}_o^M + \mathscr{P}_c$ (%)	0.5	-2.8	-1.1

4.3 Parametric Sensitivity Studies

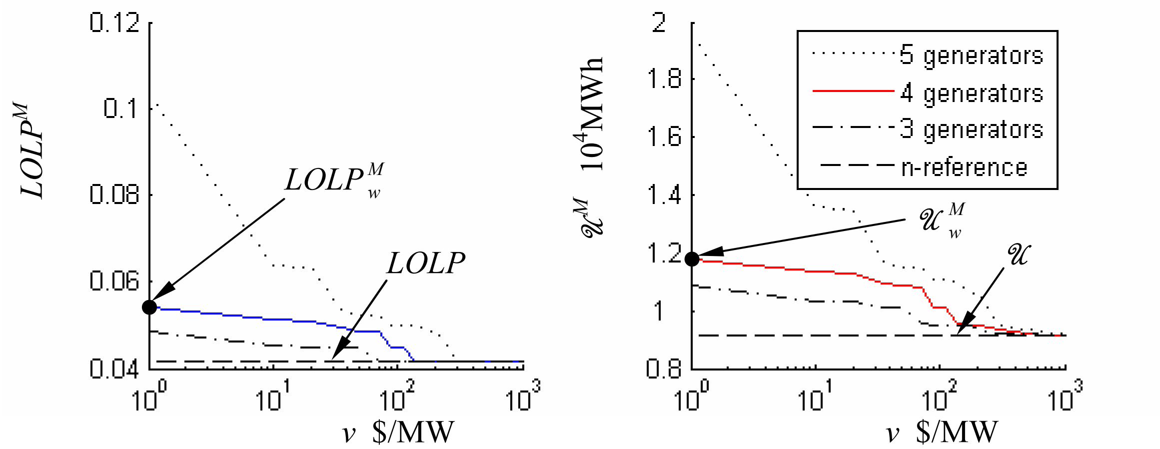
In this section we analyze the variation of the proposed program impacts with changes in the three tunable parameters: v, c_b^{max}, and m. We start with the study of the sensitivity of reliability and economic metric values with respect to changes in the penalty coefficient v, when the capacity credits c_b bought in the CCM are kept constant. We then examine the changes in the reliability and economic metric values when the CCM parameters c_b^{max} and m are changed and the penalty coefficient v is kept constant. We finish with the analysis of the changes in the reliability and CERM economic metric values for changes in c_b when v is kept constant.

We start with the sensitivity of $LOLP^M$ and $\mathscr{U}^M$ with respect to changes in the penalty coefficient v. The capacity credits c_b are kept constant at 1600 MW for test system A, 3650 MW for test system B, and 17800 MW for test system C. The numerical results are plotted in Figures 4.5 – 4.7. We also plot the n-reference case metrics for reference purposes. Without a penalty, i.e., $v = 0$ \$/MW, there is no program enforcement and so there is no change in the reliability from that of the w-reference case. Perfect compliance is attained at $v = 900$ \$/MW in test system A, and at $v = 1000$ \$/MW in test system B. These penalty coefficients are significantly smaller than the bounds $\overline{v}$ in (3.12), which take the values 60 000 \$/MW and 56 000 \$/MW for test system A and B, respectively. Also, note that in these test systems perfect compliance is attained with $c_b < \ell^p$. For test system C, compliance is relatively high with $v = 130$ \$/MW, which is significantly smaller than the bound $\overline{v}$, which takes the value 150 000 \$/MW. We note that the effectiveness of the penalty is dependent on the system characteristics.



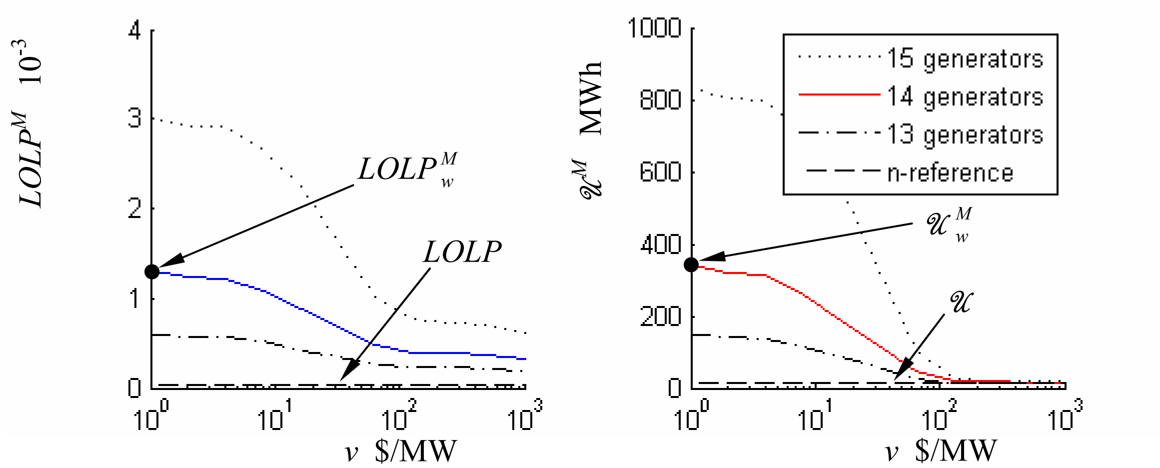
(a) ***(b)***

Figure 4.5: Adequacy metric values as a function of v \$/MW for test system A: *(a)* $LOLP^M$, *(b)* $\mathscr{U}^M$. The legend shows the number of generators controlled by the strategic seller.



(a) ***(b)***

Figure 4.6: Adequacy metric values as a function of v \$/MW for test system B: *(a)* $LOLP^M$, *(b)* $\mathscr{U}^M$. The legend shows the number of generators controlled by the strategic seller.

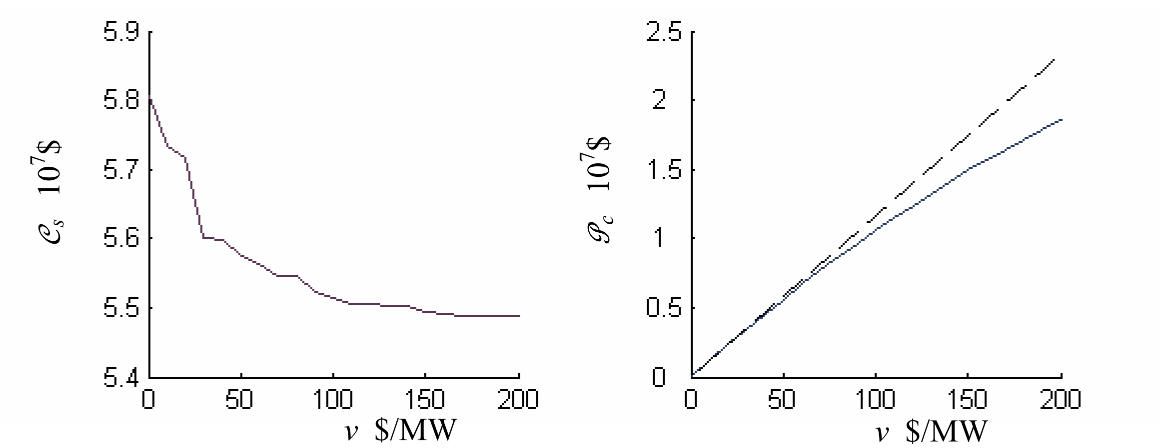


(a) ***(b)***

Figure 4.7: Adequacy metric values as a function of v \$/MW for test system C: *(a)* $LOLP^M$, *(b)* $\mathscr{U}^M$. The legend shows the number of generators controlled by the strategic seller.

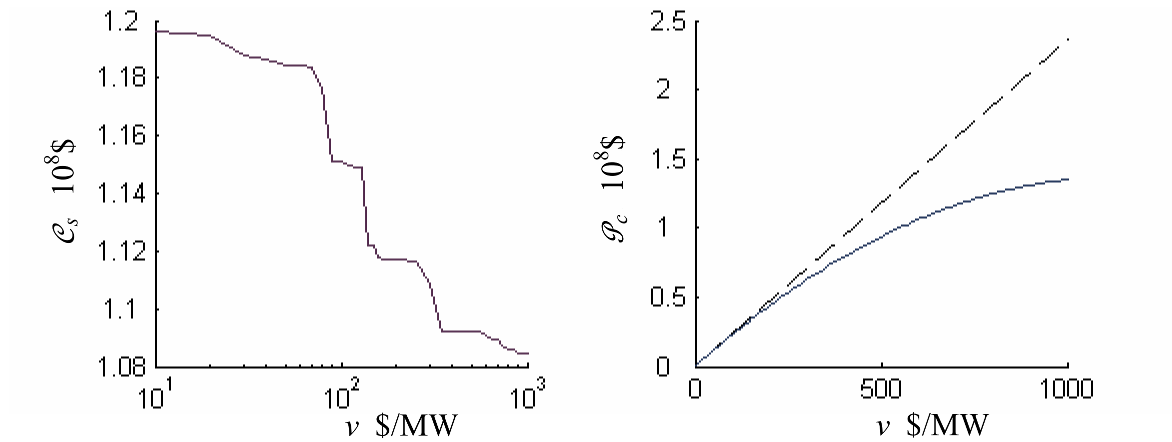
If the strategic seller changes its resource mix, the resource adequacy metrics change their value. To see this, we also considered the cases with the strategic seller having one extra generator (the generators that used to belong to seller s^5 for test system A, to s^8 for test system B, and to s^5 for test system C), and one generator less (the 100 MW generator for test system A, the 150 MW generator for test system B, and the 300 MW generator for test system C). The results are plotted in Figures 4.5 – 4.7. As the strategic seller increases its market share, resource adequacy is decreased. This is expected since the amount of capacity that can be physically withheld is increased.

We study the sensitivity of $\mathcal{C}_s$ and $\mathcal{P}_c$ to changes in v. The results are presented in Figures 4.8 – 4.10. The costs of capacity credits to each seller are found to be proportional to the penalty coefficient, and so the dependence of $\mathcal{P}_c$ on v is quadratic. For small v, we approximate this quadratic function by a linear function.



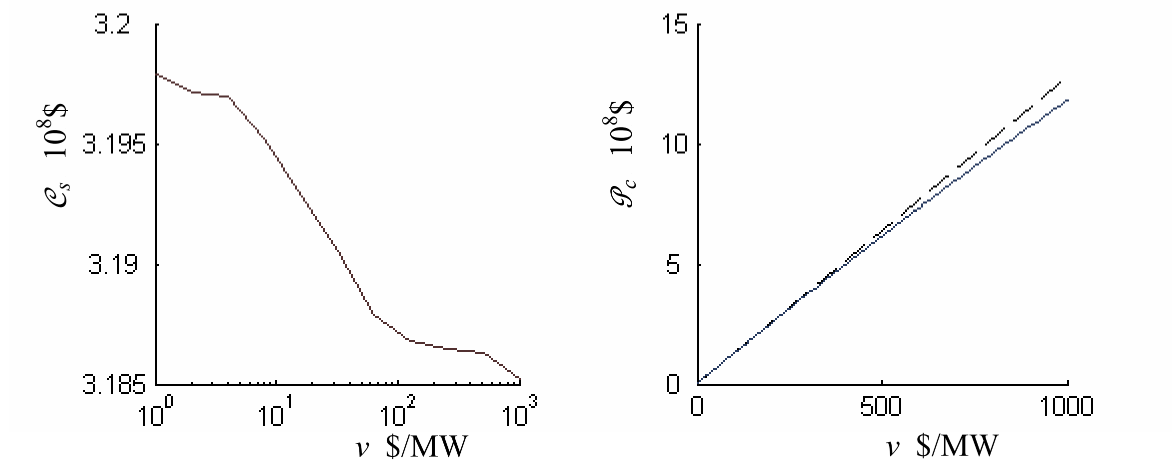
(a) *(b)*

Figure 4.8: Market metric values as a function of v \$/MW for test system A: *(a)* $\mathcal{C}_s$, and *(b)* $\mathcal{P}_c$. The broken line in *(b)* shows the linear approximation of $\mathcal{P}_c$ around the origin.



(a) ***(b)***

Figure 4.9: Market metric values as a function of v \$/MW for test system B: *(a)* $\mathcal{C}_s$ and *(b)* $\mathcal{P}_c$. The broken line in *(b)* shows the linear approximation of $\mathcal{P}_c$ around the origin.



(a) ***(b)***

Figure 4.10: Market metric values as a function of v \$/MW for test system C : *(a)* $\mathcal{C}_s$ and *(b)* $\mathcal{P}_c$. The broken line in *(b)* shows the linear approximation of $\mathcal{P}_c$ around the origin.

We next investigate the linkages between the dollars paid and the reliability improvements, and the choice of an optimal penalty coefficient v^* for given values of c_b^{max} and *m*. To do so we choose the objective function to be the total costs. That is, we measure reliability using $\mathcal{C}_o^M$, and each \$ of expected outage is assigned the same weight as each \$ of payments in the CERM or in the CCM. We show the plot of the total costs in Figures 4.11(a), 4.12(a), and 4.13 (a). We approximate the total costs by a polynomial which takes the values $\hat{\mathcal{C}}_s + \hat{\mathcal{C}}_o^M + \hat{\mathcal{P}}_c$ and use the approximation in the computation of v^*.

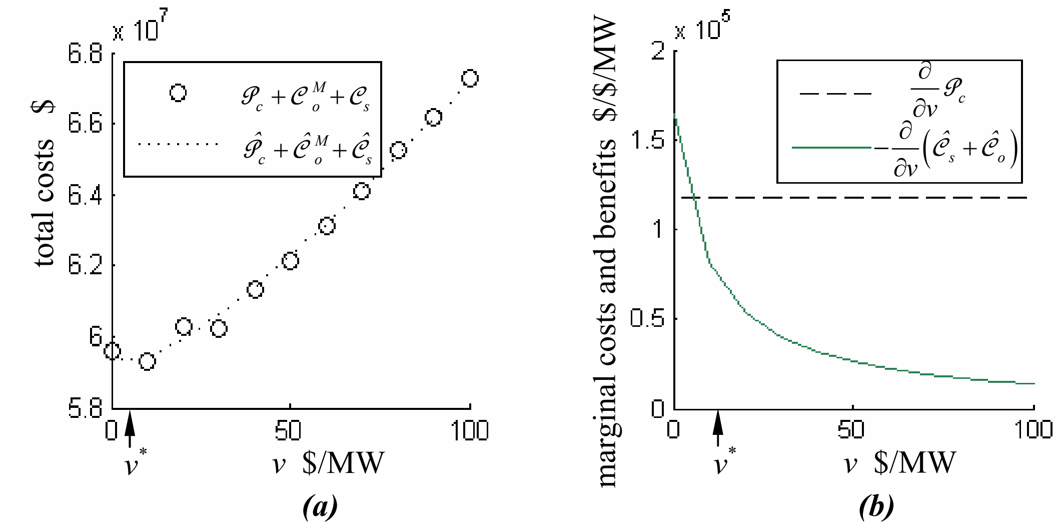


Figure 4.11: Optimal penalty coefficient for test system A: *(a)* total costs, and *(b)* marginal costs & benefits.

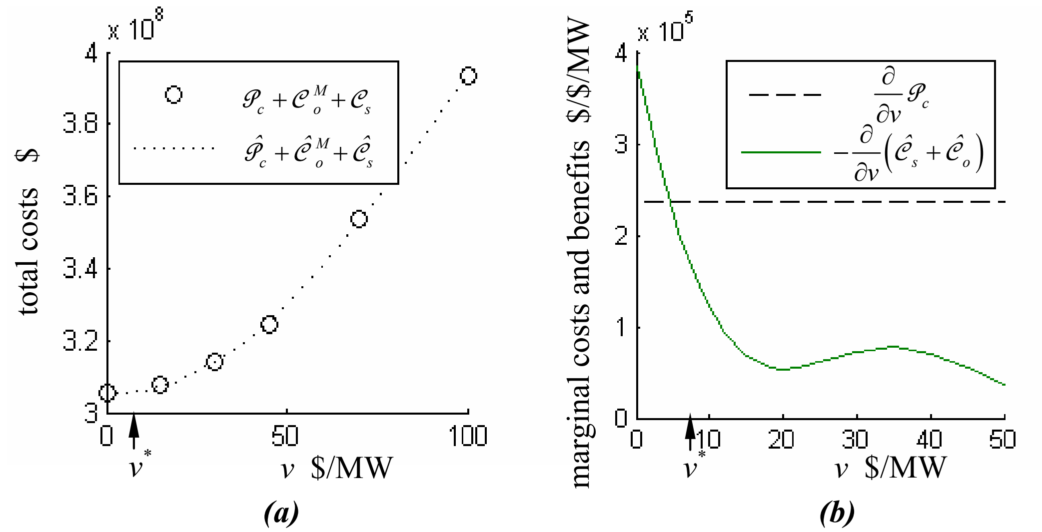


Figure 4.12: Optimal penalty coefficient for test system B: *(a)* total costs, and *(b)* marginal costs & benefits.

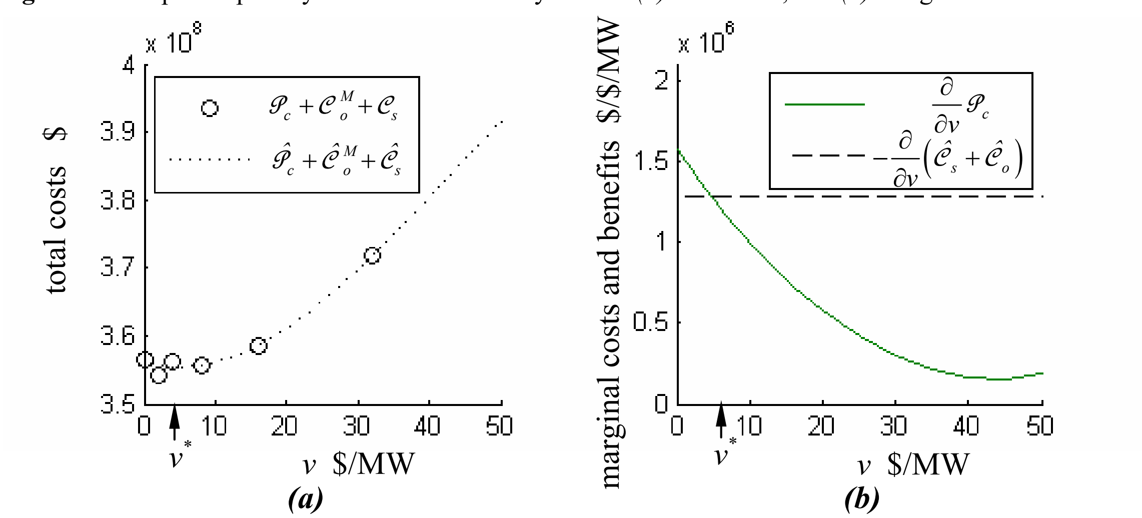
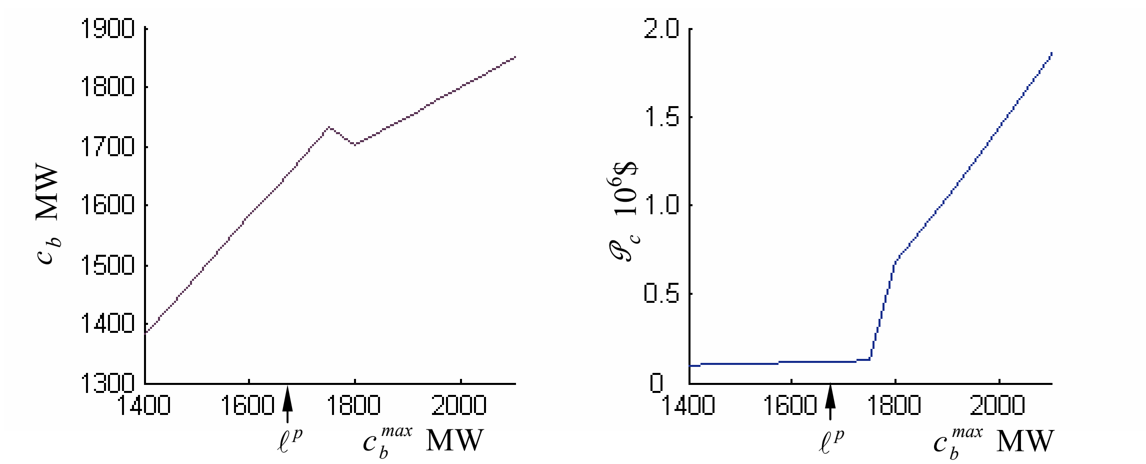


Figure 4.13: Optimal penalty coefficient for test system C: *(a)* total costs, and *(b)* marginal costs & benefits.

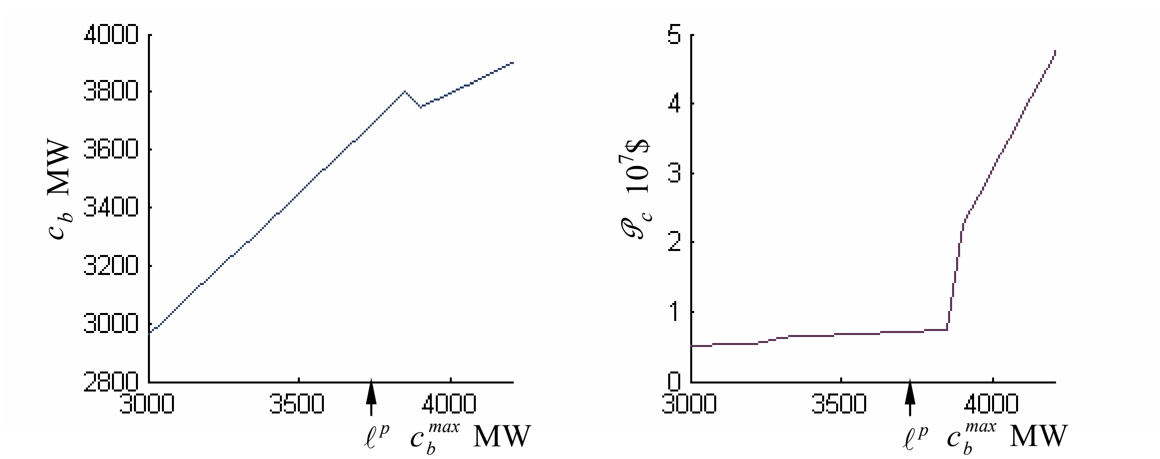
This approximation is needed because the discrete nature of load and available capacity r.v.'s results in discontinuities of the total costs when a parameter is changed. By inspection, the fitting polynomial is convex, and so the optimal penalty coefficient is that for which the derivative of the total costs is zero. We provide an interpretation of the optimal penalty coefficient v^* using Figures 4.11(b), 4.12(b), and 4.13(b). For $v < v^*$, an increase in the penalty coefficient reduces $\mathcal{C}_o^M + \mathcal{C}_s$ more than the corresponding increase in $\mathcal{P}_c$. The total costs are therefore reduced. For $v > v^*$, an increase in the penalty coefficient reduces $\mathcal{C}_o^M + \mathcal{C}_s$ more than the corresponding increase in $\mathcal{P}_c$. The total costs are therefore increased. We see that for each test system, there is a range for *v* such that the design implementation reduces the total costs for the given values of *m* and c_b^{max}. Hence, besides improving reliability the design implementation may decrease the total costs. Also, we note that the optimal penalty coefficients in the three cases are below 10 \$/MW, which is considerably smaller than the CERM price caps.

We next analyze the sensitivity of the amount of capacity credits c_b bought by the ISO and the capacity costs with respect to changes in c_b^{max}. The parameters *v* and *m* are kept constant at the values given in Table 4.3. An increase in c_b^{max} is equivalent to moving the CCM demand curve upwards, and so it can be interpreted as a bonus incentive. The numerical results for test system A are in Figure 4.14. We see that when $c_b^{max} < 1800$ MW, the strategic seller behaves as a price taker in the CCM. However, when $c_b^{max} \geq 1800$ MW, the strategic player exercises market power in the CCM. This exercise of market power has a large impact on the capacity credits costs, which get more than doubled with respect to when market power is not exercised. Moreover, this market power exercise decreases c_b and so resource adequacy is worsened. Hence, a bonus incentive may hurt resource adequacy, thus defeating the purpose of giving the bonus incentive. The results for test system B, plotted in Figure 4.15, are similar to those obtained for test system A. The results for test system C, shown in Figure 4.16, indicate that the strategic seller does not withhold capacity from the CCM for $16\ 500 \le c_b^{max} \le 19\ 000$ MW.



(a) *(b)*

Figure 4.14: Program metric values as a function of c_b^{max} for test system A: *(a)* c_b and *(b)* $\mathcal{P}_c$.



(a) *(b)*

Figure 4.15: Program metric values as a function of c_b^{max} for test system B: *(a)* c_b and *(b)* $\mathcal{P}_c$.

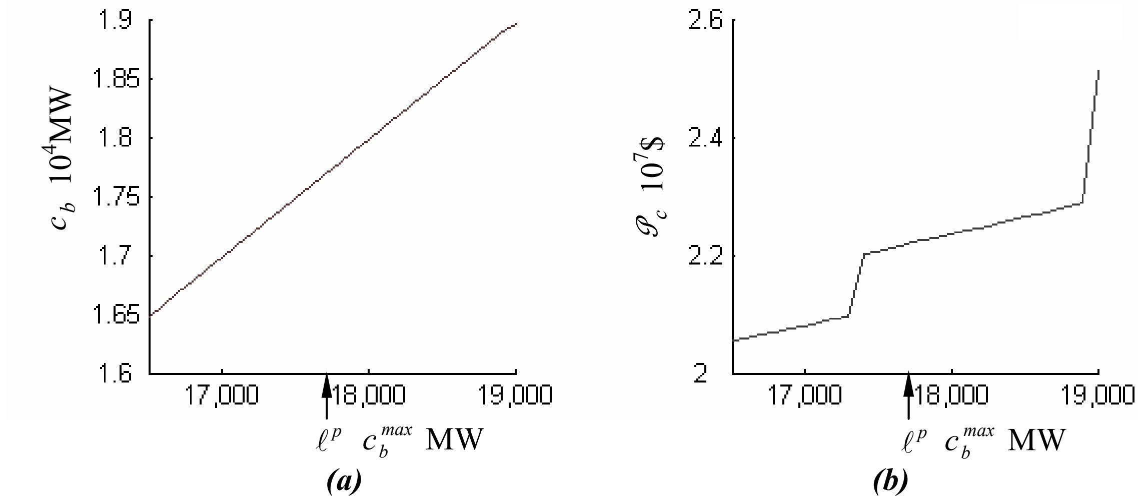


Figure 4.16: Program metric values as a function of c_b^{max} for test system C: *(a)* c_b and *(b)* $\mathscr{P}_c$.

We analyze the sensitivity of c_b and $\mathscr{P}_c$ to changes in the slope of the capacity credits demand curve *m*. The parameters *v* and c_b^{max} are kept constant at the values given in Table 4.3. The numerical results are in Figures 4.17 – 4.19. We see that when *m* is small, e.g., $m < 5$ \$/MW^2, increasing *m* brings a very large increase in c_b and $\mathscr{P}_c$. For all three test systems, as we keep increasing *m*, the changes in c_b and $\mathscr{P}_c$, although positive, become negligible: c_b and $\mathscr{P}_c$ are bounded. This means that the strategic seller behaves as a price taker in the CCM. However, this is not the case in general. In Figure 4.20 we show the variation of c_b and $\mathscr{P}_c$ with *m* when the strategic seller's market share is 19.8%. In this case, when *m* is made sufficiently large, i.e., $m > 24$, the strategic seller exercises market power in the CCM. The exercise of market power in the CCM has a large impact on the capacity credits costs. Moreover, this market power exercise decreases c_b and so resource adequacy is worsened. We see that the choice of *m* involves a trade-off: *m* needs to be "large enough" to have c_b large enough, but needs to be "low enough" to preclude the exercise of market power.

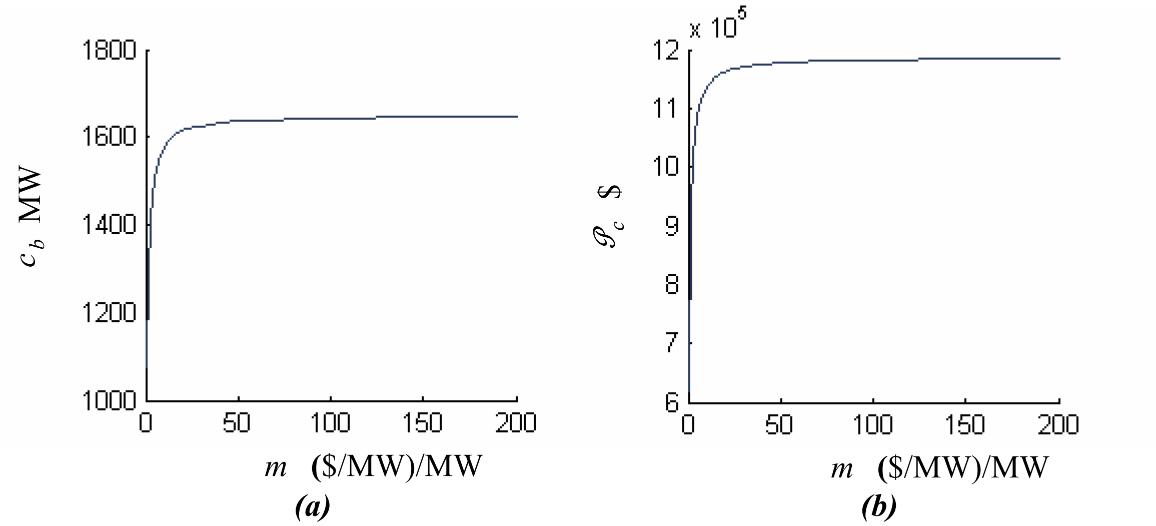


Figure 4.17: Program metric values as a function of m for test system A: *(a)* c_b and *(b)* $\mathscr{P}_c$.

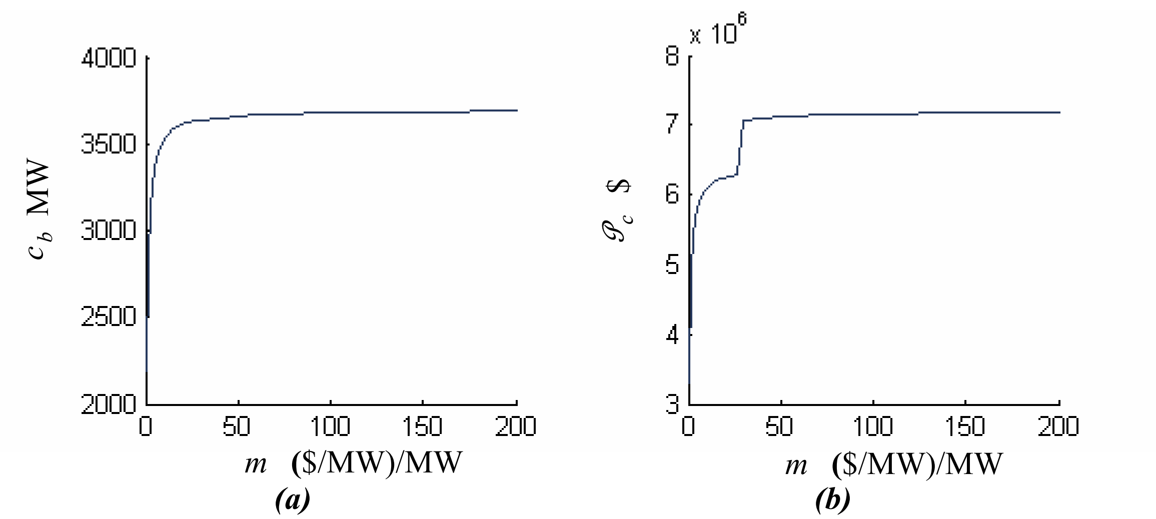


Figure 4.18: Program metric values as a function of m for test system B: *(a)* c_b and *(b)* $\mathscr{P}_c$.

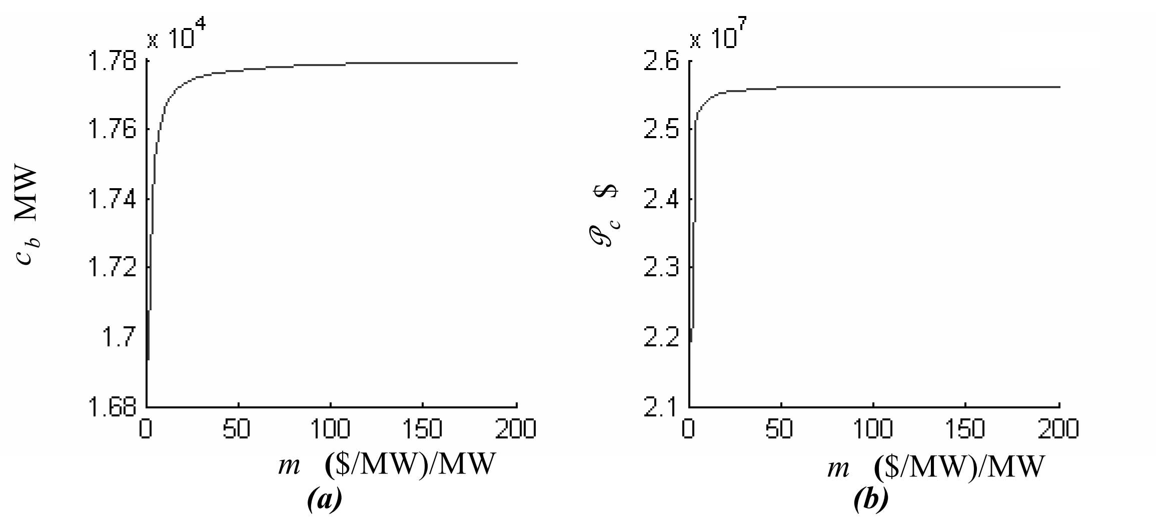


Figure 4.19: Program metric values as a function of m for test system C: *(a)* c_b and *(b)* $\mathscr{P}_c$.

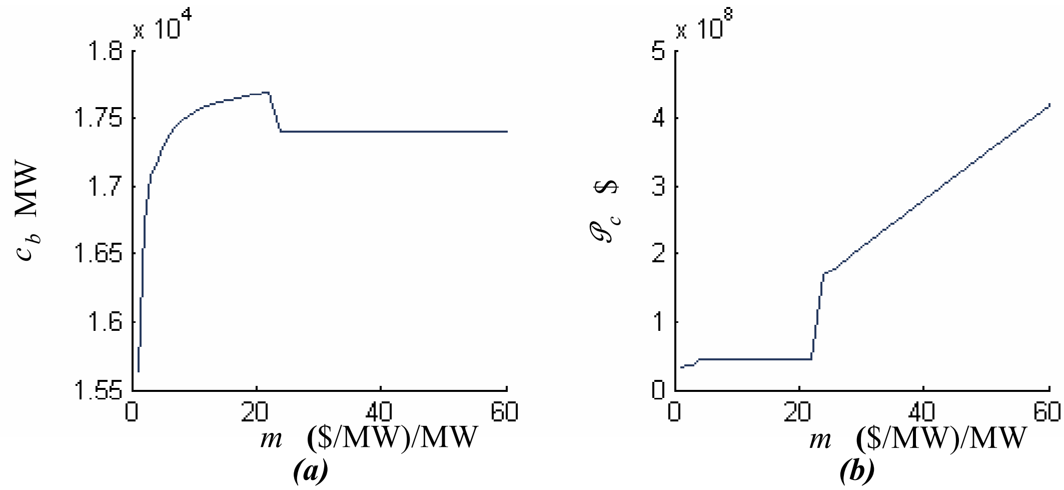
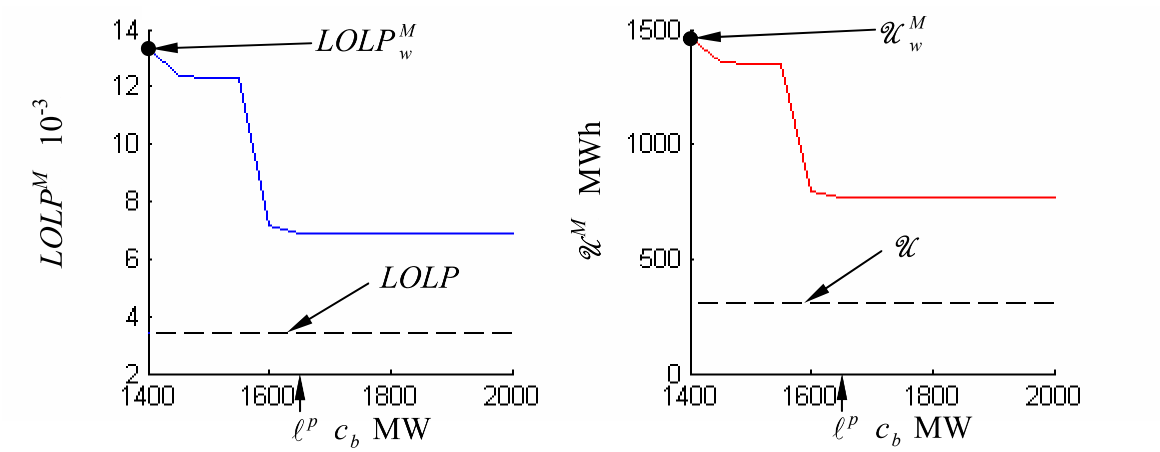


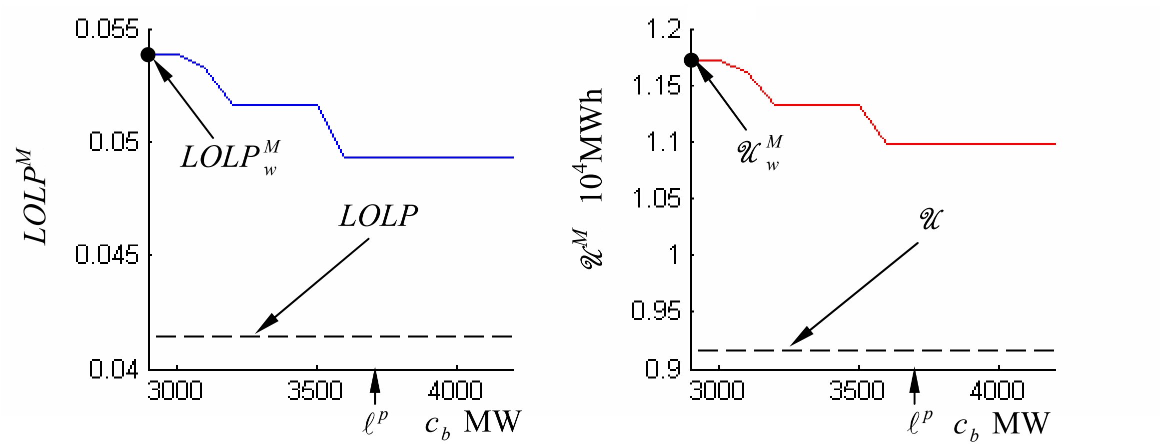
Figure 4.20: Program metric values as a function of *m* for test system C when the strategic seller has the market share increased from 11.8 to 19.8% : *(a)* c_b and *(b)* $\mathscr{P}_c$.

The changes in m and c_b^{max} bring about variations in c_b, and so we study the sensitivity of $\mathscr{U}^M$ and $LOLP^M$ to changes in the amount c_b of capacity credits bought in the monthly CCM with the penalty coefficient v kept constant at the values given in Table 4.3. The plots of the numerical results are in Figures 4.21 – 4.23. We also plot the nonmarket based metric values in broken lines for reference purposes. We note that for c_b in the order of $0.8\,\ell^p$, the reliability is the same as that of the w-reference case. For $c_b = \ell^p$, $\mathscr{U}^M$ and $LOLP^M$ are larger than $\mathscr{U}$ and $LOLP$, and so there is not perfect compliance with the penalty coefficients used. If we increase c_b above ℓ^p we obtain no further reliability improvements in the smaller test systems (A and B); this does not hold for test system C.



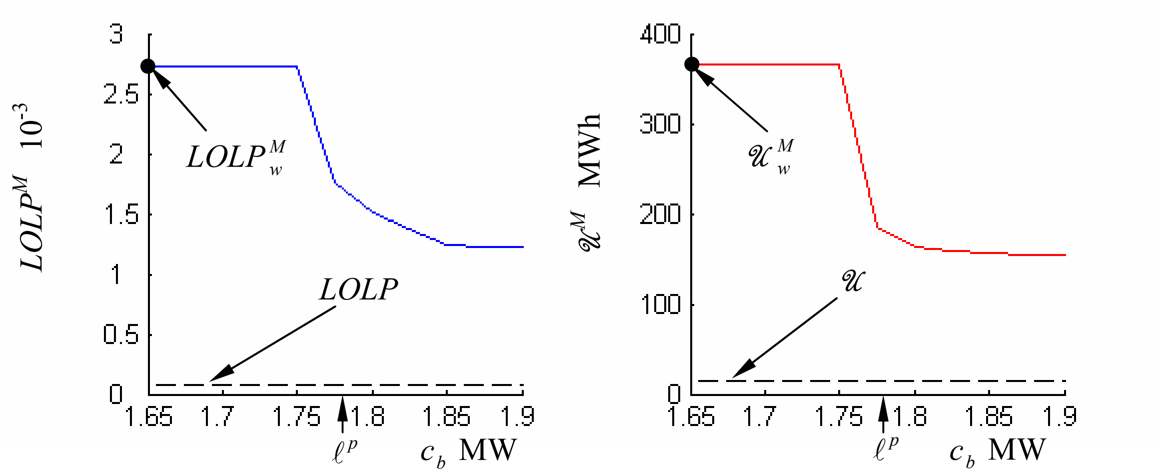
(a) *(b)*

Figure 4.21: Adequacy metric values as a function of c_b for test system A: *(a)* $LOLP^M$, and *(b)* $\mathscr{U}^M$.



(a) *(b)*

Figure 4.22: Adequacy metric values as a function of c_b for test system C: *(a)* $LOLP^M$ and *(b)* $\mathscr{U}^M$.



(a) *(b)*

Figure 4.23: Adequacy metric values as a function of c_b for test system C: *(a)* $LOLP^M$, and *(b)* $\mathscr{U}^M$.

We analyze the sensitivity of the c.d.f. of $\underset{\sim}{R}^{M}$ to changes in c_b in test system A; the numerical results are displayed in Figure 4.24. As c_b increases, the $\underset{\sim}{R}^{M}$ c.d.f. shifts right towards the c.d.f. of $\underset{\sim}{R}$, and so $P\left\{\underset{\sim}{R}^{M} \leq r\right\}$ decreases for $-0.1 \leq r \leq 0.4$ when c_b increases from 1600 to 2000 MW. For $r > \dfrac{c_b}{\ell^m} - 1$, penalties do not have any impact and so the distribution of $\underset{\sim}{R}^{M}$ is equal to that of w-reference case. We note the same jump behavior as in Figure 4.21.

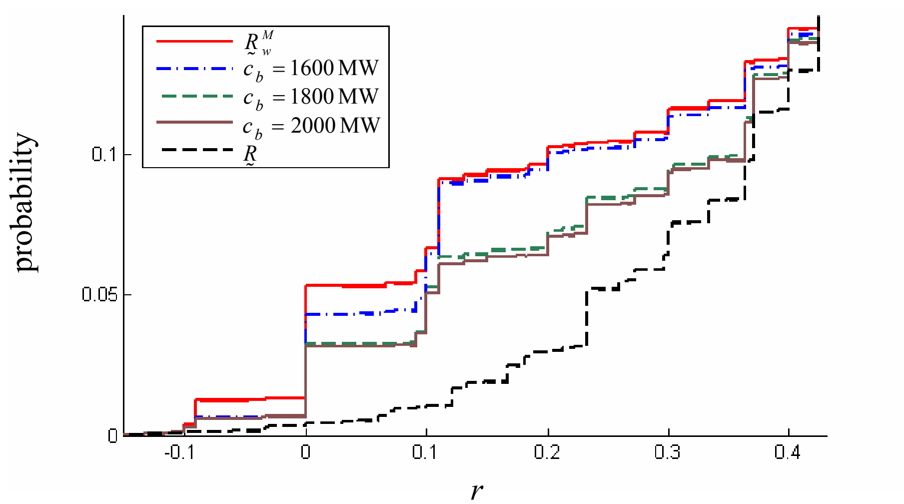


Figure 4.24: Resource availability margin c.d.f. for test system A for various values of c_b.

We study the changes in $\mathcal{C}_s$ as c_b is varied. The numerical results are presented in Figures 4.25 and 4.26, where we observe the increase in CERM efficiency as c_b increases.

4.4 Summary

In this chapter, we have analyzed the results of simulations performed on three representative and distinct test systems. These results serve to assess the impacts of the proposed resource adequacy program on the system reliability in the period of interest.

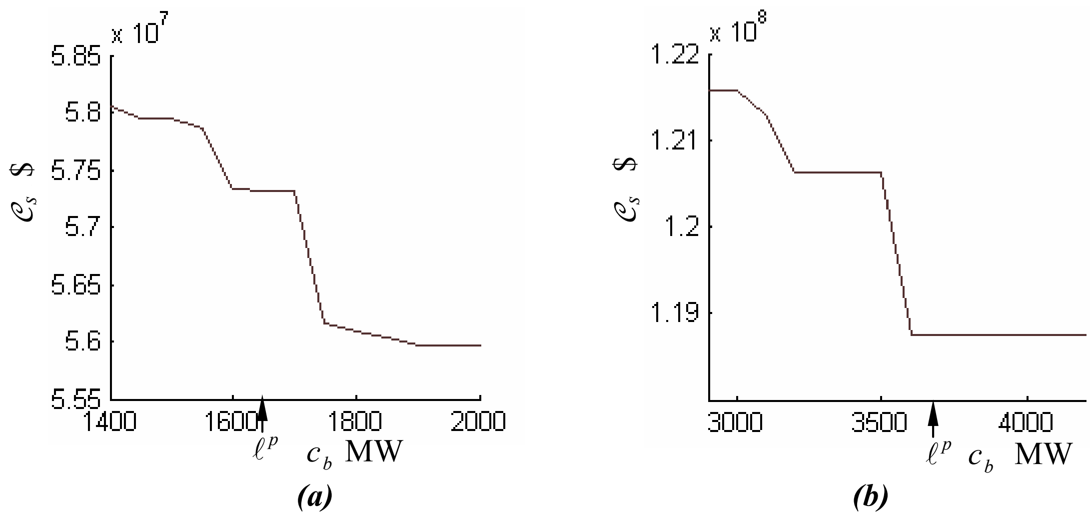


Figure 4.25: Service costs as a function of c_b: *(a)* test system A, and *(b)* test system B.

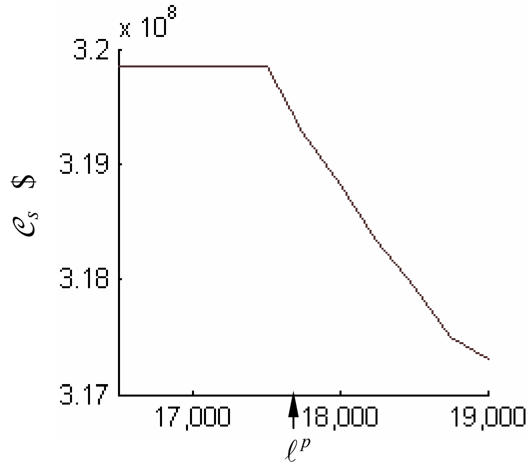


Figure 4.26: Service costs for test system C as a function of c_b.

We found in all three systems that the strategic seller has incentives to physically withhold capacity when the reserves are tight, and that the reliability is hurt by the physical withholding of capacity. We also observed that the implementation of the proposed design brings large reliability improvements in the test systems. The linkages between reliability improvements and economics were very clear using the sensitivity results with respect to changes in the penalty coefficient *v*. In all cases tested, an increase in the penalty coefficient led to improvements in reliability and CERM efficiency up to a certain value, where perfect compliance is attained, but to an increase in the costs of capacity. Therefore, the choice of v involves a trade-off between the costs and the reliability improvements. A relatively small penalty coefficient of the order of 1/15 of the energy market price cap was found to be optimal in the sense of minimizing total costs in the three test systems. An increase in the maximum amount of capacity credits bought (bonus incentive) and in the (negative of the) slope of the capacity credits demand curve did not necessarily imply an improvement in system reliability, although it certainly rose $\mathscr{P}_c$. This is due to the possibility of market power exercise in the CCM. In the three test systems $c_b^{max} = \ell^p$ worked well in terms of avoiding market power exercise and improving system reliability. The largest impacts of the proposed design implementation were in the reliability metrics. CERM efficiency improved but not nearly as much as the reliability did.

CHAPTER 5

CONCLUSIONS

In this chapter, we give a summary of the work reported in this thesis and discuss some natural extensions of the presented research results.

5.1 Summary

In this thesis, we have studied the short-term resource adequacy problem and investigated the impacts of market outcomes on system reliability. In particular, we have proposed a design of a short-term resource adequacy program. This work constitutes the first effort in the design and analysis of a short-term resource adequacy program to discourage physical capacity withholding with appropriate incentive/disincentive mechanisms. We presented the nature of the problem in Chapter 1.

We described the modeling aspects in Chapter 2. We reviewed the models of the physical loads and generation resources and their representation in the day-ahead combined energy and reserves markets. We specifically focused on the role and behavior of generators as market players. We reviewed the well-known metrics for resource adequacy and adapted them to incorporate the market outcomes for reliability evaluation in the market environment.

We devoted Chapter 3 to the presentation of the proposed design of a short-term resource adequacy program. The design uses a *carrots and sticks* approach that gives incentives for providing capacity to markets and metes out penalties for nonperformance situations. A salient characteristic of the proposed program is the effective linking of the market economics with the reliability improvements. The design is based on the specified capacity requirements which the program formulates in terms of available capacity. Two key aspects of the program design are the appropriate formulation of the price-dependent available capacity requirements and the tuning of the penalty coefficient. The analysis of the proposed design shows that the program can improve system reliability when the requirements formulation and penalty value are judiciously selected. We presented a simple implementation of the proposed design to allow the assessment of the resulting short-term resource adequacy. The analysis provided gives a good basis for the selection of appropriate parameters of the proposed program.

We provided results of the program on three distinct test systems. We tested each system under a wide variety of conditions to study a large number of cases. In each case of each system tested, we found that the implementation of the design results in reliability improvements. An interesting observation is that an increase in the penalty coefficient in some easily determined range not only increases program costs but also improves reliability. We also found that an increase in the capacity requirements above a system dependent level can lead to poorer reliability in the presence of market power exercise in the capacity credits markets. Extensive sensitivity studies show that improved reliability and reduced total system costs can be attained with the proposed program when the tunable parameters are judiciously selected.

The design and analysis work of this thesis serves as a useful aid in the assessment and enhancement of short-term resource adequacy programs.

5.2 Future Work

The work reported constitutes a basis for the further study of issues related to resource adequacy in a competitive environment over short- and long-term time frames.

There are several clear extensions to the work presented here. These relate to modeling aspects, design extensions, and implementation issues in the short-term time frame. Moreover, the extension of the work to long-term resource adequacy remains a critical need for the industry in the competitive environment.

The modeling aspects include the relaxation of simplifying modeling assumptions, extensions of the models discussed, and the inclusion of new models. In the modeling description, we neglected the demand responsiveness to price, multiple player interaction, and transmission network effects. The future work needs to address the incorporation of these aspects into the models. The active participation of the demand-side players in the market needs to be taken into account. In actual electricity markets there is usually more than one strategic player, and so the extensions of the player behavior models to capture the impacts of the interaction of the players in each market provide another area for future work. The work presented focused on the generation and load aspects of the adequacy problem, all transmission constraints were ignored and the area under consideration was considered islanded. In reality, the transmission network has an impact in resource adequacy, and so its inclusion in the problem is of great importance. The analysis was done using a combined energy and reserves market model. As there is no single market design in the various jurisdictions, the incorporation of different market models is needed. In this thesis, all intertemporal effects were ignored. The use of load and the available generation models that realistically capture the inter-temporal effects, and the inclusion of intermarket in the player behavior models is important.

With the extended modeling described above, the basic design can be further extended to include the capacity credits providers' geographical location and the price responsiveness characteristics of the various demand-side players. These design enhancements are worthy of attention as the transmission network congestion occurs rather frequently, and some demand-side players respond to prices in the short-term.

Another area for further research is issues related to the implementation of the resource adequacy programs. The formulation and analysis of different *(i)* market compatible capacity requirements that appropriately account for the benefits capacity provides to the system, and *(ii)* effective penalty schemes that provide the desired disincentives for noncompliance, are clearly important aspects of the design of a resource adequacy program. Also, there is a need to investigate the market power opportunities arising with the design implementation and their impact on resource adequacy, and to devise mitigation schemes to discourage/prevent them, whenever applicable.

On a long-term basis, the problem of generation investment in electricity markets is worthy of attention. The role of resource adequacy programs as providers of incentives for investments is of particular importance. The work reported here deals exclusively with short-term resource adequacy, and so the longer term impacts of the proposed program, such as investments, are beyond the scope of the work. The relationship between short-term resource adequacy programs and longer term issues addresses important aspects of completing the market design.

APPENDIX A

ACRONYMS AND NOTATION

A.1 Acronyms and Abbreviations

CERM	:	Combined Energy and Reserves Market
CCM	:	Capacity Credits Market
FERC	:	Federal Energy Regulatory Commission
NERC	:	North-American Electric Reliability Council
ISO	:	Independent System Operator
ISO-NE	:	New England Independent System Operator
NYISO	:	New York Independent System Operator
PJM	:	Pennsylvania, New Jersey, and Maryland Interconnection
NETA	:	New Energy Trading Agreement
SMD	:	Standard Market Design
NOPR	:	Notice Of Proposed Rulemaking
ICAP	:	Installed Capacity
LOLP	:	Loss Of Load Probability
LSE	:	Load Serving Entity

A.2 Notation

The following are the key aspects of the notation used:

- All variables are in *italics*
- All random variables are in upper case with a tilde $\utilde{\ }$ underneath.

- All vectors are <u>underlined</u> ***bold***.
- The superscript * refers to an optimal solution
- The superscript M refers to market-based quantities
- The subscript T refers to total quantities
- The superscript max refers to maximum values
- The subscript e refers to energy
- The subscript r refers to reserves
- The subscript c refers to capacity credits
- The subscript b refers to bought quantities

The list of indices is:

$h = 1, 2, ..., H$	:	hour index
$d = 1, 2, ..., D$	:	demand class index
$j = 1, 2, ..., G^i$	:	generation unit index
$n = 1, 2, ..., B$	:	buyer index
$i = 1, 2, ..., S$	:	seller index
$k = 1, 2, ..., \beta$	:	block offer index in the CERM

The sets used are:

$\{1, 2, ..., H\}$	:	set of hours
$\mathbb{T}_d$	:	subset of hours in demand class d
$\mathbb{B} = \{b^1, b^2, ..., b^B\}$	:	set of buyers
$\mathbb{S} = \{s^1, s^2, ..., s^S\}$	:	set of sellers
$\Gamma^i = \{\underline{\boldsymbol{\sigma}}^i, \underline{\boldsymbol{\varsigma}}^i, \underline{\boldsymbol{\kappa}}^i\}$	:	seller i's offer in the CERM

The constants and parameters used are:

H_d	:	number of hours of demand class *d*
ℓ_d	:	deterministic component of the demand class *d*, in MW
δ_d	:	reserves bought in the CERM in demand class *d,* in MW
p_d	:	probability that the uncertain component of the demand class *d* is zero
ℓ^p	:	maximum demand, in MW
ℓ^m	:	minimum demand, in MW
g_j^i	:	installed capacity of generator *j* of seller s^i, in MW
g^i	:	installed capacity of seller s^i, in MW
g	:	installed capacity in the system, in MW
a_j^i	:	availability of generator *j* of seller s^i, in p.u.
$\overline{\rho}_e$	:	energy price cap, in \$/MWh
$\overline{\rho}_r$	:	reserves price cap, in \$/MW
$\overline{\rho}_e^i$	:	seller s^i's energy offer price cap, in \$/MWh
$\overline{\rho}_e^i$	:	seller s^i's reserves offer price cap, in \$/MW
w	:	value of lost load or willingness-to-pay, in \$/MWh
v	:	penalty on non-complying capacity credit suppliers, in \$/MW
c_b^{max}	:	maximum capacity credits demanded, in MW
m	:	capacity credit demand curve slope, in (\$/MW)/MW

The variables used are:

e_j^{ik}	:	energy sold by seller s^i from offered block *k* of generator *j*, in MWh
$\underline{\boldsymbol{e}}_j^i$	:	vector of e_j^{ik} s
$\underline{\boldsymbol{e}}^i$	:	vector composed of the vectors $\underline{\boldsymbol{e}}_j^i$
$\underline{\boldsymbol{e}}$	:	vector composed of the vectors $\underline{\boldsymbol{e}}^i$

e^{i}_{jT} : total energy sold by seller s^{i} from unit j, in MWh

e^{i}_{T} : total energy sold by seller s^{i}, in MWh

r^{ik}_{j} : reserves sold by seller s^{i} from offered block k of generator j, in MW

$\underline{\boldsymbol{r}}^{i}_{j}$: vector of r^{ik}_{j} s

$\underline{\boldsymbol{r}}^{i}$: vector composed of the vectors $\underline{\boldsymbol{r}}^{i}_{j}$

$\underline{\boldsymbol{r}}$: vector composed of the vectors $\underline{\boldsymbol{r}}^{i}$

r^{i}_{jT} : total reserves sold by seller s^{i} from unit j, in MW

r^{i}_{T} : total reserves sold by seller s^{i}, in MW

c^{i} : capacity credits provided by seller s^{i}, in MW

$\underline{\boldsymbol{c}}$: vector of c^{i} s

c_{b} : capacity credits bought by the ISO, in MW

ρ_{e} : energy market clearing price, in \$/MWh

ρ_{r} : reserves market clearing price, in \$/MW

ρ_{c} : capacity credit market clearing price, in \$/MW

σ^{ik}_{j} : energy offer price of offer block k from generator j of seller s^{i}, in \$/MWh

ξ^{i} : capacity credits offered by seller s^{i}, in MW

$\underline{\boldsymbol{\xi}}$: vector of capacity credits offered

$\underline{\boldsymbol{\sigma}}^{i}_{j}$: vector of σ^{ik}_{j} s

ς^{ik}_{j} : reserves offer price of offer block k from generator j of seller s^{i}, in \$/MW

$\underline{\boldsymbol{\varsigma}}^{i}_{j}$: vector of ς^{ik}_{j} s

π^{ik}_{j} : reserve capacity of offer block k of generator j of seller s^{i}, in MW

$\underline{\boldsymbol{\pi}}^{i}_{j}$: vector of π^{ik}_{j} s

$\underline{\boldsymbol{\pi}}^{i}$: vector composed of the vectors $\underline{\boldsymbol{\pi}}^{i}_{j}$ s

$\underline{\boldsymbol{\pi}}$: vector composed of the vectors $\underline{\boldsymbol{\pi}}^{i}$ s

κ_j^{ik} : capacity of offer block k of generator j of seller s^i, in MW

$\underline{\boldsymbol{\kappa}}_j^i$: vector of κ_j^{ik} s

$\underline{\boldsymbol{\kappa}}^i$: vector composed of the vectors $\underline{\boldsymbol{\kappa}}_j^i$ s

$\underline{\boldsymbol{\kappa}}$: vector composed of the vectors $\underline{\boldsymbol{\kappa}}$ s

κ^i : seller s^i total offered capacity in the CERM, in MW

The random variables used are:

$\underset{\sim}{L}$: load demand, in MW

$\Delta \underset{\sim}{L}_d$: random load demand component of demand class d, in MW

$\underset{\sim}{A}_j^i$: available capacity of generator j of seller s^i, in MW

$\underset{\sim}{A}^i$: seller s^i 's available capacity, in MW

$\underset{\sim}{A}$: total available capacity in the system, in MW

$\underset{\sim}{K}$: capacity offered in the energy and reserves market, in MW

The realization of these random variables are denoted by

α_j^i : available capacity of generator j of seller s^i, in MW

α^i : available capacity of seller s^i, in MW

α : total available capacity, in MW

$\Delta \ell_d$: random load demand component of demand class d, in MW

ℓ : load demand, in MW

κ : total capacity offered in the market, in MW

The functions used are:

$\mathscr{C}(\cdot,\cdot)$: expected costs of serving the CERM demand, in \$

$\Pi_d^i(\cdot,\cdot)$: expected profits of seller s^i in demand class *d*, in \$

$\chi_e^i(\cdot)$: seller s^i's energy production costs in \$

$\chi_r^i(\cdot)$: seller s^i's reserves production costs, in \$

$\chi_c^i(\cdot)$: seller s^i's capacity credits costs, in \$

$\lambda_e^{i0}(\cdot,\cdot)$: energy price when $\Delta \underset{\sim}{L}_d = 0$ as a function of e^i and r^i, in \$/MWh

$\lambda_e^{\hat{i}\delta}(\cdot,\cdot)$: energy price when $\Delta \underset{\sim}{L}_d = \delta_d$ as a function of e^i and r^i, in \$/MWh

$\lambda_r^i(\cdot,\cdot)$: reserves price as a function of e^i and r^i, in \$/MW

$\mathscr{S}(\cdot,\cdot)$: social welfare in the CCM, in \$

$\vartheta^i(\cdot)$: integral of the marginal offer price in the CCM for seller s^i, in \$

$\phi(\cdot)$: capacity credit market demand curve, in \$/MW as a function of the quantity

$\Psi(\cdot,\cdot)$: penalty function for hourly capacity credit providers, in \$/MW

The metrics defined and used in the report are:

$\underset{\sim}{R}$: resource availability margin

LOLP : loss of load probability

$\mathscr{U}$: expected unserved energy, in MWh

$\mathscr{E}$: expected energy demanded, in MWh

$\mathcal{C}_o$: expected outage costs, in \$

$\mathcal{C}_s$: expected service costs, in \$

$\mathscr{P}_c$: monthly capacity costs, in \$

APPENDIX B

CERM OFFER CONSTRUCTION

In this appendix we give an algorithm for the determination of an offer Γ^{i*} that ensures that seller s^i sells e^{i*} and r^{i*} while satisfying the offer cap constraints. The amounts to sell e^{i*} and r^{i*} are obtained from (2.39). We assume the units are ordered in increasing costs and only the available units are considered. The maximum capacity constraints are taken care of in the solution of (2.36).

Step 0 Initialize $e = 0,\ r = 0,\ j = 1$.

Step 1 If

$$e + g_j^i < e^{i*},$$

add block $\left\{0, \overline{\rho}_r^i, g_j^i\right\}$ to the offer, set $e = e + g_j^i$, $j = j + 1$ and repeat step 1.

Step 2 If

$$e < e^{i*},$$

add block $\left\{0,\ \overline{\rho}_r^i, e^{i*} - e\right\}$ to the offer.

Step 3 If

$$g_j^i - \left(e^{i*} - e\right) < r^{i*},$$

add block $\left\{\overline{\rho}_e^i,\ 0,\ g_j^i - \left(e^{i*} - e\right)\right\}$ to the offer and set $j = j + 1$.

Else add block $\left\{\overline{\rho}_e^i,\ 0,\ r^{i*}\right\}$ to the offer and go to step 6.

Step 4 If

$$r + g_j^i < r^{i*},$$

add block $\left\{\overline{\rho}_e^i,\ 0,\ g_j^i\right\}$ to the offer, set $r = r + g_j^i$, $j = j + 1$ and repeat step 4.

Step 5 If

$$r < r^{i*},$$

add block $\left\{\bar{\rho}_e^i, 0, r^{i*} - r\right\}$ to the offer.

Step 6 If

$$\lambda_e^{i0}\left(e^i, r^i\right) > \bar{\rho}_e^i,$$

or

$$\lambda_r^i\left(e^i, r^i\right) > \bar{\rho}_r^i,$$

stop (physically withhold capacity).

Else, offer all remaining capacity at offer price caps to economically withhold.

APPENDIX C

CAPACITY CREDITS COST DETERMINATION

C.1 Hourly Capacity Credits Costs

The costs $\chi_c^i\left(c^i\right)$ for the c^i MW of hourly capacity credits provided by seller s^i consist of:

- penalties due to forced outages;
- penalties due to voluntary capacity withholding (exercise of market porwer);
- reduction in market power opportunities (lost opportunity cost); and
- payments for trading the obligation.

We derive an upper bound for the hourly capacity credit costs (worst case) by neglecting the possibility of trading the obligation, or, equivalently, assuming the obligation trade price is v \$/MW.

From (3.15), the profits in the CERM for providing e^i MWh of energy and r^i MW of reserves together with the impacts of the CCM commitment are denoted by

$$\breve{\Pi}_d^i\left(e^i,r^i,\kappa_T^i,c^i\right)=\Pi_d^i\left(e^i,r^i\right)-max\left\{c^i-\kappa_T^i,0\right\}\cdot v\,. \tag{C.1}$$

Let $\hat{\Pi}_d^i\left(c^i\right)$ be the profit when s^i optimizes its strategy subject to providing c^i MW of capacity credits,

$$\hat{\Pi}_d^i\left(c^i\right)=\max_{e^i,r^i,\kappa_T^i}\breve{\Pi}_d^i\left(e^i,r^i,\kappa_T^i,c^i\right). \tag{C.2}$$

$\hat{\Pi}_d^i\left(\cdot\right)$ is a monotonically nonincreasing function, since the set of feasible strategies when c^i MW of capacity credits are provided includes the set of feasible strategies when

$c^{i\prime} > c^i$ MW of capacity credits are provided, and the penalties are nonnegative. The costs $\chi_c^i\left(c^i\right)$ are obtained by taking the difference

$$\chi_c^i\left(c^i\right) = \hat{\Pi}_d^i\left(0\right) - \hat{\Pi}_d^i\left(c^i\right). \tag{C.3}$$

If $\hat{\Pi}_d^i\left(\cdot\right)$ is a differentiable function at c^i, the marginal costs are

$$\left.\frac{d\chi_c^i\left(c\right)}{dc}\right|_{c=c^i}. \tag{C.4}$$

Otherwise, we approximate the marginal costs of c MW of hourly capacity credits by taking the difference

$$\hat{\Pi}_d^i\left(c^i - c\right) - \hat{\Pi}_d^i\left(c^i\right). \tag{C.5}$$

If seller s^i is a price taker, seller s^i has no advantage in withholding its available resources from the energy and reserves market. Then, the only positive costs of providing capacity credits are the expected penalties charged due to forced outages of seller s^i's resources,

$$\begin{aligned}\chi_c^i\left(c^i\right) &= E\left\{v\,max\left(c^i - \underset{\sim}{A}^i, 0\right)\right\}\\ &= vE\left\{c^i - \underset{\sim}{A}^i \middle| c^i \geq \underset{\sim}{A}^i\right\} P\left\{c^i \geq \underset{\sim}{A}^i\right\}\\ &= v\int_0^{c^i}\left(c^i - y\right)dF_{\underset{\sim}{A}^i}\left(y\right),\end{aligned} \tag{C.6}$$

where $F_{\underset{\sim}{A}^i}\left(\cdot\right)$ is the the c.d.f. of $\underset{\sim}{A}^i$, $F_{\underset{\sim}{A}^i}\left(y\right) = P\left\{\underset{\sim}{A}^i \leq y\right\}$. Thus, the marginal costs are

$$\begin{aligned}\left.\frac{d\chi_c^i\left(c\right)}{dc}\right|_{c=c^i} &= v\int_0^{c^i} dF_{\underset{\sim}{A}^i}\left(y\right)\\ &= vF_{\underset{\sim}{A}^i}\left(c^i\right).\end{aligned} \tag{C.7}$$

The marginal costs of capacity credits are proportional to $F_{\underline{A}^i}(\cdot)$ for price takers, so for price takers, the marginal costs are a nondecreasing function. This is not necessarily true for strategic sellers, as we see in the simulation results. If seller s^i only owns unit *j*, then for any $c^i \leq g_j^i$,

$$\left.\frac{d\chi_c^i(c)}{dc}\right|_{c=c^i} = v\left(1-a_j^i\right). \tag{C.8}$$

Figure C.1 gives an example of the hourly capacity credits costs for price takers.

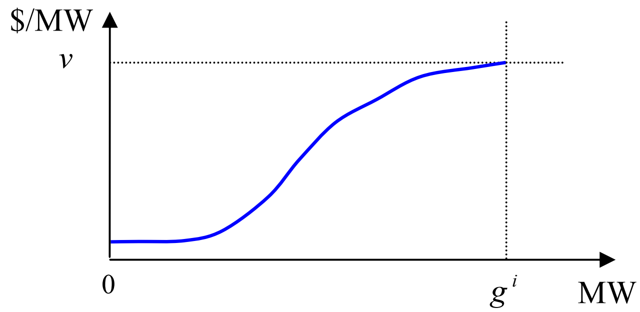


Figure C.1: Price taker seller s^i capacity credits costs.

C.2 Monthly Capacity Credits Costs

The monthly capacity credits costs are the sum of the hourly capacity credits costs for all hours of the month. For the price taker, the hourly capacity credits costs are independent of the hour in question, so the costs of c^i MW monthly capacity credits are

$$H \cdot \chi_c^i\left(c^i\right), \tag{C.9}$$

where *H* is the number of hours in the month.

APPENDIX D

TEST SYSTEM DATA

We assume that the available capacities of two different generation units are independent of each other. We further assume the available capacity of each generation resource is independent of the load demand.

The number of hours in the period is $H = 720$. The strategic seller is s^1 and $s^2, s^3, ..., s^S$ are price takers. The factor ζ for price takers is $\zeta = 0.1$. The marginal production costs are constant and equal to f_j^i \$/MWh for generator *j* of seller *i*. The market price caps for all systems are in Table D.1.

Table D.1: Market price cap data

$\bar{\rho}_e$	150 \$/MWh
$\bar{\rho}_r$	30 \$/MW

D.1 Test System A

The expected energy demanded is $\mathcal{E}_A = 1,008\ 10^3$MWh. The willingness-to-pay of consumers is $w = 1000$ \$/MWh. There are 8 generation companies, $\mathcal{S} = \{s^1, s^2, ..., s^8\}$, and 10 generation units. The demand data is detailed in Table D.2, and the seller and generation unit data is presented in Table D.3.

Table D.2: Demand data for test system A

d	1	2	3
H_d	144	288	288
ℓ_d MW	1500	1350	1000
δ_d MW	150	150	150
p_d	0.6	0.6	0.6

Table D.3: Seller and generation unit data for test system A

s^i	$\bar{\rho}_e^i$ \$/MWh	$\bar{\rho}_r^i$ \$/MW	j	g_j^i MW	a_j^i	f_j^i \$/MWh	σ_j^{i1} \$/MWh	ς_j^{i1} \$/MW
$s^{\hat{1}}$	70	30	1	400	0.99	15	-	-
			2	250	0.95	20	-	-
			3	100	0.99	30	-	-
s^2	20	2	1	500	0.90	10	11.0	1.0
s^3	30	5	1	400	0.95	25	27.5	2.5
s^4	40	7	1	250	0.99	35	38.5	3.5
s^5	70	12	1	150	0.92	60	66.0	6.0
s^6	82	15	1	100	0.90	71	78.1	7.1
s^7	95	16	1	100	0.90	80	88.0	8.0
s^8	100	20	1	100	0.93	83	91.3	8.3

D.2 Test System B

The expected energy demanded is $\mathcal{E}_B = 2{,}242\ 10^3$MWh. The willingness-to-pay of consumers is $w = 1000$ \$/MWh. There are 9 generation companies, $\mathcal{S} = \{s^1, s^2, ..., s^9\}$, and 12 generation units. The demand data is detailed in Table D.4, and the seller and generation unit data is presented in Table D.5.

Table D.4: Demand data for test system B

d	1	2	3
H_d	144	324	252
ℓ_d MW	3500	3000	2350
δ_d MW	200	250	200
p_d	0.75	0.65	0.70

Table D.5: Seller and generation unit data for test system B

s^i	$\overline{\rho}_e^i$ \$/MWh	$\overline{\rho}_r^i$ \$/MW	j	g_j^i MW	a_j^i	f_j^i \$/MWh	σ_j^{i1} \$/MWh	ς_j^{i1} \$/MW
s^1	70	30	1	350	0.96	20	-	-
			2	150	0.95	45	-	-
			3	50	0.94	60	-	-
			4	50	0.94	70	-	-
s^2	15	5	1	700	0.91	10	11.0	1.0
s^3	16	5	1	600	0.92	11	12.1	1.1
s^4	19	5	1	500	0.93	15	16.5	1.5
s^5	21	5	1	500	0.93	18	19.8	1.8
s^6	29	8	1	400	0.94	25	27.5	2.5
s^7	42	8	1	400	0.94	35	38.5	3.5
s^8	45	8	1	250	0.96	37	40.7	3.7
s^9	55	9	1	250	0.96	45	49.5	4.5

D.3 Test System C

The expected energy demanded is $\mathcal{E}_C = 7\,658\,640$ MWh. The willingness-to-pay of consumers is $w = 100\,000$ \$/MWh. There are 87 generation companies, $\mathcal{S} = \{s^1, s^2, ..., s^{87}\}$, and 100 generation units. The demand data is detailed in Table D.6, and the seller and generation unit data is presented in Table D.7.

Table D.6: Demand data for test system C

d	1	2	3	4	5
H_d	216	180	144	108	72
ℓ_d MW	6100	8400	12 200	15 900	17 500
δ_d MW	400	300	300	300	300
p_d	0.60	0.60	0.60	0.60	0.60

Table D.7: Seller and generation unit data for test system C

s^i	$\bar{\rho}_e^i$ \$/MWh	$\bar{\rho}_r^i$ \$/MW	j	g_j^i MW	a_j^i	f_j^i \$/MWh	σ_j^{i1} \$/MWh	ς_j^{i1} \$/MW
$s^{\hat{1}}$	90	30	1	500	0.94	12	-	-
			2	400	0.99	14	-	-
			3	250	0.95	21	-	-
			4	250	0.95	21	-	-
			5	200	0.93	25	-	-
			6	300	0.96	29	-	-
			7	100	0.99	31	-	-
			8	100	0.94	44	-	-
			9	100	0.96	49	-	-
			10	50	0.95	51	-	-
			11	50	0.94	60	-	-
			12	50	0.95	63	-	-
			13	50	0.94	70	-	-
			14	100	0.92	75	-	-
s^2	15	2	1	500	0.91	10	11.3	1.3
s^3	16	2	1	500	0.9	10	11.3	1.3
s^4	17	2	1	700	0.91	10	11.3	1.3
s^5	18	2	1	450	0.93	11	12.43	1.43
s^6	19	2	1	400	0.99	11	12.43	1.43
s^7	20	2	1	600	0.92	11	12.43	1.43
s^8	21	2	1	250	0.99	13	14.69	1.69
s^9	22	2	1	350	0.94	13	14.69	1.69
s^{10}	23	3	1	400	0.99	15	16.95	1.95
s^{11}	24	3	1	350	0.92	15	16.95	1.95
s^{12}	25	3	1	500	0.93	15	16.95	1.95
s^{13}	26	3	1	200	0.95	15	16.95	1.95
s^{14}	27	3	1	350	0.92	16	18.08	2.08

Table D.7 continued.

s^{15}	28	3	1	500	0.98	18	20.34	2.34
s^{16}	29	3	1	500	0.93	18	20.34	2.34
s^{17}	30	3	1	250	0.90	19	21.47	2.47
s^{18}	31	3	1	350	0.96	20	22.6	2.6
s^{19}	32	4	1	300	0.96	21	23.73	2.73
s^{20}	33	4	1	200	0.97	21	23.73	2.73
s^{21}	34	4	1	300	0.97	22	24.86	2.86
s^{22}	35	4	1	150	0.98	24	27.12	3.12
s^{23}	36	4	1	250	0.97	25	28.25	3.25
s^{24}	37	4	1	400	0.95	25	28.25	3.25
s^{25}	38	4	1	400	0.94	25	28.25	3.25
s^{26}	39	4	1	250	0.98	25	28.25	3.25
s^{27}	40	4	1	200	0.96	25	28.25	3.25
s^{28}	41	5	1	250	0.95	27	30.51	3.51
s^{29}	42	5	1	200	0.94	29	32.77	3.77
s^{30}	43	5	1	150	0.9	30	33.9	3.9
s^{31}	44	5	1	250	0.9	31	35.03	4.03
s^{32}	45	5	1	300	0.9	31	35.03	4.03
s^{33}	46	5	1	150	0.91	31	35.03	4.03
s^{34}	47	5	1	100	0.91	32	36.16	4.16
s^{35}	48	5	1	250	0.94	32	36.16	4.16
s^{36}	49	5	1	100	0.99	34	38.42	4.42
s^{37}	50	5	1	250	0.93	34	38.42	4.42
s^{38}	51	5	1	250	0.99	35	39.55	4.55
s^{39}	52	5	1	400	0.94	35	39.55	4.55
s^{40}	53	5	1	250	0.94	35	39.55	4.55
s^{41}	54	5	1	200	0.93	35	39.55	4.55
s^{42}	55	5	1	100	0.97	36	40.68	4.68
s^{43}	56	5	1	250	0.96	36	40.68	4.68
s^{44}	57	5	1	250	0.96	37	41.81	4.81

Table D.7 continued.

s^{45}	58	5	1	150	0.98	37	41.81	4.81
s^{46}	59	6	1	100	0.98	38	42.94	4.94
s^{47}	60	6	1	100	0.96	39	44.07	5.07
s^{48}	61	6	1	175	0.96	39	44.07	5.07
s^{49}	62	6	1	200	0.94	39	44.07	5.07
s^{50}	63	6	1	300	0.98	40	45.2	5.2
s^{51}	64	7	1	175	0.91	44	49.72	5.72
s^{52}	65	7	1	250	0.96	45	50.85	5.85
s^{53}	66	7	1	100	0.94	45	50.85	5.85
s^{54}	67	7	1	300	0.93	46	51.98	5.98
s^{55}	68	7	1	100	0.97	48	54.24	6.24
s^{56}	69	7	1	100	0.91	49	55.37	6.37
s^{57}	70	7	1	100	0.96	49	55.37	6.37
s^{58}	71	7	1	175	0.95	49	55.37	6.37
s^{59}	72	7	1	100	0.94	50	56.5	6.5
s^{60}	73	7	1	300	0.93	50	56.5	6.5
s^{61}	74	7	1	75	0.92	51	57.63	6.63
s^{62}	75	7	1	50	0.91	53	59.89	6.89
s^{63}	76	7	1	150	0.95	53	59.89	6.89
s^{64}	77	7	1	50	0.98	55	62.15	7.15
s^{65}	78	7	1	50	0.97	56	63.28	7.28
s^{66}	79	8	1	50	0.96	57	64.41	7.41
s^{67}	80	8	1	150	0.95	57	64.41	7.41
s^{68}	81	8	1	100	0.93	58	65.54	7.54
s^{69}	82	8	1	50	0.94	58	65.54	7.54
s^{70}	83	8	1	50	0.88	60	67.8	7.8
s^{71}	84	8	1	150	0.92	60	67.8	7.8
s^{72}	85	8	1	200	0.93	60	67.8	7.8
s^{73}	86	8	1	250	0.92	64	72.32	8.32
s^{74}	87	8	1	150	0.91	69	77.97	8.97

Table D.7 continued.

s^{75}	88	9	1	100	0.95	71	80.23	9.23
s^{76}	89	9	1	100	0.9	71	80.23	9.23
s^{77}	90	9	1	100	0.96	75	84.75	9.75
s^{78}	91	9	1	50	0.94	76	85.88	9.88
s^{79}	92	9	1	50	0.93	80	90.4	10.4
s^{80}	93	10	1	100	0.9	80	90.4	10.4
s^{81}	94	10	1	50	0.98	80	90.4	10.4
s^{82}	95	10	1	250	0.97	80	90.4	10.4
s^{83}	96	11	1	50	0.96	82	92.66	10.66
s^{84}	97	12	1	25	0.91	83	93.79	10.79
s^{85}	98	15	1	100	0.93	83	93.79	10.79
s^{86}	99	20	1	150	0.92	87	98.31	11.31
s^{87}	100	30	1	25	0.9	102	115.26	13.26

REFERENCES

[1] Glossary of Terms Task Force, *Glossary of Terms*, North American Electric Reliability Council, Princeton, NJ, August 1996, www.nerc.com/pub/sys/all_updl/docs/pubs/glossv10.pdf.

[2] J. Endrenyi, *Reliability Modeling in Electric Power Systems*. New York, NY: Wiley, 1978, p. 120.

[3] J. Perloff, *Microeconomics*, 2nd ed. Boston, MA: Addison – Wesley, 2001.

[4] Maryland Senate Bill 300: Electricity Utility Industry Restructuring, Passed April 1999, p. 3, mlis.state.md.us/1999rs/billfile/sb0300.htm.

[5] C. D. J. Waters, *Inventory Control and Management*. New York: John Wiley & Sons, 1992, p. 319.

[6] W. Viscusi, J. Vernon and J. Harrington, *Economics of Regulation and Antitrust*, 2nd ed. Cambridge, MA: The MIT Press, 1998, p. 323.

[7] R. Wilson, "Architecture of power markets," *Econometrica*, vol. 70, pp. 1299 – 1340, July 2002.

[8] S. Stoft, *Power System Economics: Designing Markets for Electricity*. Piscataway, NY: IEEE Press, 2002.

[9] "Standard Market Design notice of proposed rulemaking," Federal Energy Regulatory Commission, Washington, DC, July 31, 2002, www.ferc.gov/industries/electric/indus-act/smd/nopr.asp.

[10] L. Ruff, "Competitive electricity markets: Why they are working and how to improve them," National Economics Research Associates, New York, 12 May 1999, p. 27, faculty-gsb.stanford.edu/wilson/archive/E542 /classfiles/ruff0512.pdf.

[11] "ISO New England outlines market solutions to secure long-term reliability for the region," Press Release, ISO New England Inc., Holyoke, MA, August 31st, 2004, www.iso-ne.com/ISO_news/2004_Archive/Press_Statement_Locational_ICAP_FERC_Filing_August_2004.pdf.

[12] "Market behavior rules," Federal Energy Regulatory Commission, Washington, DC, Docket Nos. EL01-118-000 and EL01-118-001, November 17, 2003. www.ferc.gov/legal/ferc-regs/land-ord-elec.asp.

[13] "Order clarifying market behavior rules," Federal Energy Regulatory Commission, Washington, DC, Docket Nos. EL01-118-003, May 19, 2004, www.ferc.gov/legal/ferc-regs/land-ord-elec.asp.

[14] K. Hays, "Transcripts: Market manipulation was sport," The Associated Press, New York, June 2, 2004.

[15] P. Joskow and E. Kahn, "A quantitative analysis of pricing behavior in California's wholesale electricity market during summer 2000: the final word," Massachusetts Institute of Technology, Cambridge, MA, February 4, 2002, econ-www.mit.edu/faculty/pjoskow.

[16] S. Burns and G. Gross, "Value of service reliability," *IEEE Transactions on Power Systems*, vol. 5, no. 3, pp. 825 – 834, Aug 1990.

[17] S. Oren, "Capacity payments and supply adequacy in competitive electricity markets," in *Anais do VII SEPOPE*, Curitiba, Brazil, May 2000.

[18] A. Papalexopoulos, "Supplying the generation to meet the demand," *IEEE Power & Energy Magazine,* vol. 2, no. 4, pp. 66 – 73, July-August 2004.

[19] "Reglas de funcionamiento del mercado de producción de energía eléctrica," Operador del Mercado Ibérico de Energía – Polo Español S.A., Madrid, Spain, April 2001, p. 133, http://www.omel.es.

[20] A. Chuang and F. Wu, "Capacity payments and the pricing of reliability in competitive generation markets," in *IEEE Proceedings of the 33rd Annual Hawaii International Conference on System Sciences*, January 2000.

[21] D. Newbery, "Power markets and market power," *The Energy Journal*, vol. 16, no. 3, pp. 39 – 67, 1995.

[22] C. Vazquez, M. Rivier and I. J. Perez-Arriaga, "A market approach to long-term security of supply," *IEEE Transactions on Power Systems*, vol. 17, no. 2, , pp. 349 – 357, May 2002.

[23] S. Oren, "Ensuring generation adequacy in competitive electricity markets," June 2003, www.ucei.org/Working_Papers/EPE_007.pdf.

[24] J. Hull, *Options, Futures and Other Derivatives*, 4th ed. Upper Saddle River, NJ: Prentice Hall, 2000, p. 6.

[25] *NYISO Installed Capacity Manual*, Version 4, New York Independent System Operator, Schenectady, NY, April 2003, www.nyiso.com/services/documents/manuals.

[26] *NEPOOL Manual for Installed Capacity*, Revision 5, ISO New England Inc., Holyoke, MA, Manual M-20, January 2004, www.iso-ne.com/smd/market_rule_1_and_NEPOOL_manuals/NEPOOL_Manuals/M-20_Installed_Capacity/.

[27] "Reliability assurance agreement among load serving entities in the MAAC control zone," PJM Interconnection LLC, Valley Forge, PA, November 2003, www.pjm.com/documents/downloads/agreements/raa.pdf.

[28] N. Rau, "Assignment of capability obligations to entities in competitive markets – the concept of reliability equity," *IEEE Transactions on Power Systems*, vol. 14, no. 3, pp. 884 – 889, Aug 1999.

[29] G. Shuttleworth, J. Falk, E. Meehan, M. Rosenzweig, and H. Fraser, "Electricity markets and capacity obligations: A report for the department of trade and industry," National Economics Research Associates, London, UK, December 2002, www.dti.gov.uk/energy/whitepaper/cap_study.pdf.

[30] E. Meehan, C. LaCasse, P. Kalmus, and B. Neenan, "Central resource adequacy markets for PJM, NY-ISO and NE-ISO," National Economics Research Associates, New York, NY, February 2003, www.nera.com/publication.asp?p_ID=2029.

[31] "Resolving phase 1 resource adequacy issues," California Public Utilities Commission, Sacramento, CA, November 5, 2004, www.cpuc.ca.gov/published/final_decision/41087-01.

[32] "Order on compliance filing and establishing hearing procedures," Federal Energy Regulatory Commission, Washington, DC, June 2, 2004, Docket Nos. ER03-563-030 and EL04-102-000, www.ferc.gov/EventCalendar/Files/20040602174406-ER03-563-030.pdf.

[33] "Reliability pricing model draft business rules," version 5.0, PJM Interconnection, Valley Forge, PA, January 2005, www.pjm.com/committees/working-groups/dsrwg/downloads/20050111-item-7-rpm.pdf.

[34] "Wholesale power market platform white paper," Federal Energy Regulatory Commission, Washington, DC, April 28, 2003, www.ferc.gov/industries/electric/indus-act/smd/white_paper.pdf.

[35] "Initial decision on locational installed capacity market," Federal Energy Regulatory Commission, Washington, DC, June 15, 2005, Docket No. ER03-563-030, www.ferc.gov/whats-new/hd-current/06-15-05-licap.asp.

[36] D. Kirschen and G. Strbac, *Fundamentals of Power System Economics*. West Sussex, England: John Wiley & Sons Ltd, 2004.

[37] G. Gross and D. Finlay, "Generation supply bidding in perfectly competitive electricity markets," *Computational and Mathematical Organization Theory*, vol. 6, no. 1, pp. 83 – 98, May 2000.

[38] *NEPOOL Manual for Market Operations*, Revision 9, ISO New England Inc., Holyoke, MA, Manual M-11, November 5th, 2004, www.ISO-ne.com/smd/market_rule_1_and_NEPOOL_manuals/NEPOOL_Manuals/M-11_Market_Operations/.

[39] K. Kariuki and R. Allan, "Evaluation of reliability worth and value of lost load," *IEE Proceedings – Generation, Transmission and Distribution*, vol. 143, no. 2, pp. 171 – 180, March 1996.

[40] "ISO market power mitigation measures," in *NYISO FERC Electric Tariff*, Vol. 2, New York Independent System Operator, Schenectady, NY, Attachment H, May 2004, www.nyiso.com/services/oatt.html.

[41] S. de la Torre, J. Arroyo, A. Conejo, and J. Contreras, "Price maker self-scheduling in a pool-based electricity market: A mixed-integer LP approach," *IEEE Transactions on Power Systems*, vol. 17, no. 4, pp. 1037 – 1042, November 2002.

[42] A. Baillo, M. Ventosa, M. Rivier, and A. Ramos, "Optimal offering strategies for generation companies operating in electricity spot markets," *IEEE Transactions on Power Systems*, vol. 19, no. 2, pp. 745 – 753, May 2004.