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Dynamic Investment in Electricity Markets and Its Impact on System Reliability

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Abstract

In this paper we view the problem of adequate electricity supply and demand as a dynamic process affected by several fundamental factors. By incorporating the effect of the available price signals on investment decisions we model the investment dynamics for (i) a system comprising both spot and futures (forward) markets, and for (ii) a system comprising a spot and an installed capacity (ICAP) market. In particular, we analyze the effect of timing of price information available on the dynamics of long-term supply/demand and price evolution. It is shown how by having a futures market, investment decisions to add new capacity could be executed without much delay while the investors are guaranteed revenues through long-term futures (forward) contracts. The modeling and simulations are performed using aggregate long-term price models.

Keywords: investment, reliability, forward-looking, futures (forward) prices, ICAP market, investment delay.

1. PROBLEM OF INTEREST

In the regulated industry a power company responsible for serving its load demand coordinates the planning and operations procedures. The main criteria of reliable service are met by ensuring sufficient (physical) capacity for the anticipated load demand trends (long-term adequacy), as well as sufficiently flexible power plants capable of responding to load deviations in near real time (short-term reliability). In this industry structure the price of electricity is a result (output variable) of planning and operating procedures in place; the price is only used as an average measure of total cost and not as an active signal for decision making by the individual electricity users and/or producers.

On the other hand, in an industry which attempts to be market-based, the price of electricity begins to play a fundamental role of a feedback to both the (groups of) suppliers and users of electricity as they optimize their own (distributed) profits and/or benefits. The price signals are provided by the markets, and are essential factors in shaping both the price dynamics prices as well as the physical availability of electricity.

In this paper, we first provide a broad overview of factors affecting the price dynamics and physical capacity. A general block diagram is presented which could be used for explaining phenomena like recent events in California. Next, we focus the contribution in this paper on modeling and simulating the investment process at the aggregate market level; the premise is that the investment process is driven by the price knowledge, which is directly useful for decisions to invest. This is done by using a recently developed model for long-term price dynamics; using this model we simulate prices (spot and/or futures) necessary for the decision making process to invest. The result is investment dynamics of interest.

In particular, by modeling the role of price in (i) a system comprising spot and futures markets, and in (ii) a system comprising spot and an installed capacity (ICAP) market, we analyze the effect of timing of price information availability on the dynamics of supply/demand and price evolution. In the simulation section we show that while futures (forward) markets are generally created to provide market participants a tool to hedge their individual risks, these markets also provide invaluable information (feedback) to the investors and contribute to more timely investments as these are needed. Not surprising, an investment decision based on historic data is not as good, since those historic data do not perfectly represent future demand and supply conditions. Having a futures (forward) market facilitates investment decisions to add new capacity without a significant delay while the investors are guaranteed revenues through long-term futures (forward) contracts. This leads to adequate supply and relatively stabilized market prices without the need to introduce price caps. Imposing a price cap is generally the last resort approach to "correcting" market prices. Price caps, if not temporary, would deter new investments and in turn could cause shortage of supply and would eventually threaten reliability of the system.

While some of these findings make common sense, this paper for the first time demonstrates dynamics of the process and stresses the role of price as a signal to which individual decision-makers react to the market conditions. The modeling approach taken in this paper could be generalized to include other effects of interest, such as demand price-elasticity; in this model only the effect of demand growth, without allowing for price-responsive demand, is shown through some simulations in this paper.

Possibly the biggest remaining challenge is in extending the findings of this paper, which are kept at the level of aggregate prices, to modeling prices which are result of decision making by the individual market participants. This approach, with more complexity, would allow for more realistic modeling of decision-makers and their effect on prices and investments, including strategic bidding. This work is currently in progress (Visudhiphan, Ilic (2001)).

1.1 Broad Problem Posing

Since the summer of 2000, the California market has experienced a series of supply shortages, price spikes and rolling blackouts. This has mainly been caused by the load demand outgrowing total available capacity. The lack of new investments over past several years has created a tight reserve margin situation, which together with the lack of price-responsive demand, in which consumption does not decrease when prices are skyrocketing, has resulted in serious physical shortages (reliability problems) and in a financial/political crisis (Ilic, Skantze,Visudhiphan (2001)). This situation raises a basic question concerning an adequate market design in which capacity expansion is done dynamically over time to meet the demand variations.

To prevent California-like situation from taking place in other evolving electricity markets, one can no longer rely on strictly equilibrium-type market design analysis and argue that eventually a market equilibrium may exist, an approach typically taken in the current literature, with very few exceptions (Graves et.al. (1998)). Instead, one should approach the problem of supply and demand in electricity markets as a constantly evolving process in which installed capacity is a result of individual decisions by the investors, and the near-real time supply availability is a function of how is this installed capacity used to meet the varying demand. An effective market design is the one in which meaningful investing signals are directly observable through the market; the role of such market is to encourage right investments with confidence and sufficient returns. Adding new capacity of the right technology and the right size at the right time and locations is essential to sustaining load growth, maintaining system reliability, and conforming to the unavoidable regulations (such as environmental concerns). In a competitive power industry a well-designed market begins to play a role which the utility planner has traditionally fulfilled.

In the current industry debate the role of spot electricity markets as a means of ensuring (short-term) reliability has been over-emphasized. Since currently electric power demand is nearly inelastic, small supply margin could create shortage of supply, and subsequently unavoidable price spikes and rolling blackouts. One could argue that certain regulatory enforcement such as imposing a price cap could prevent price spikes (instantaneously). However, this short-term solution is not sustainable, and it will eventually lead to insufficient revenues, which would, in turn, deter capacity expansion.

If there exists, demand elasticity would stabilize short-term market prices. However, long-term load trends are result of factors not observable on daily basis and are less likely to be directly controllable through spot pricing[1]. Without long-term provisions, inadequate supply is quite likely; this is true both when demand grows at an unexpected rate and when demand grows slower than anticipated. An installed capacity (ICAP) market, which exists in some electricity markets, is aimed to ensure sufficient short-term capacity under contingencies. But if lack of capacity expansion persists, demand for ICAP is high causing high ICAP prices. Consequently, high electricity spot prices will happen.

1.2 Approach taken in this paper

In this paper we develop an analytic approach to study questions concerning electricity market instruments which are needed to provide adequate price signals to balance supply and demand in a timely manner. We suggest that futures markets play the key role; futures provide market participants not only an instrument to hedge price risk, but are also an indicator of future supply and demand conditions, which are critical in making an investment decision.

[1] Persistently high electricity prices could discourage new electricity-intensive industries to enter the area, causing slower demand growth.

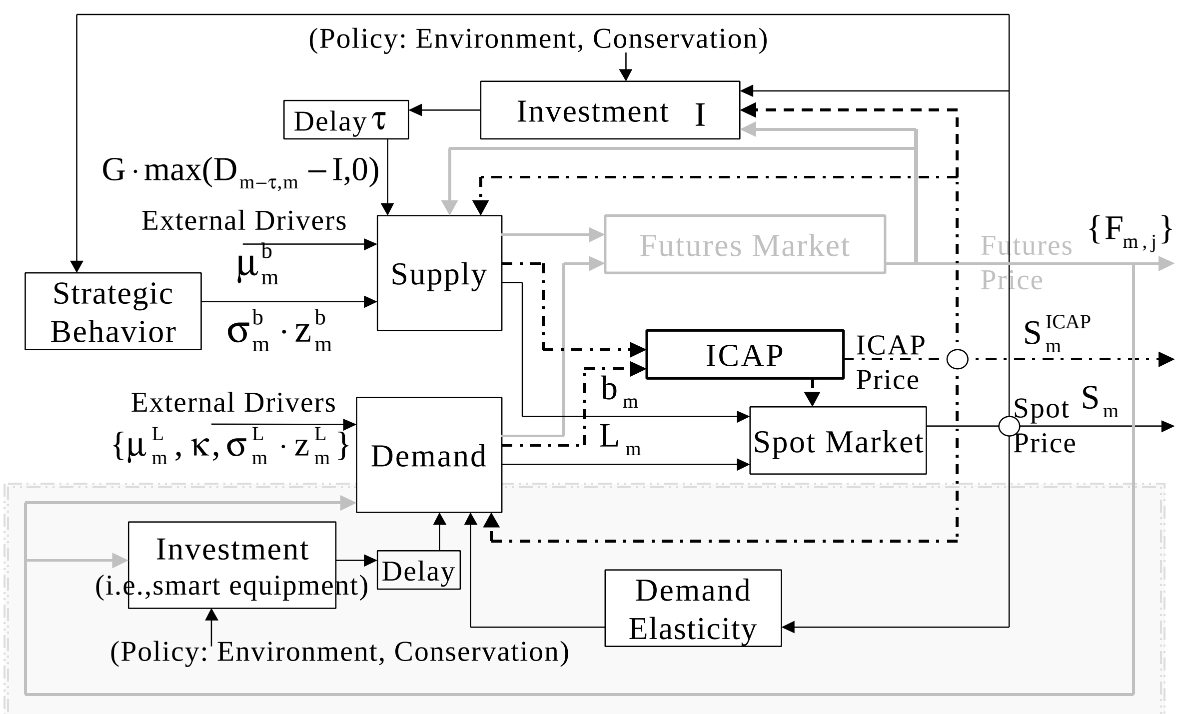
In this paper, we apply a stochastic model to analyzing long-term characteristics of electricity markets and to determining the fundamental factors contributing to (long-term) supply adequacy or scarcity that could threaten system reliability. This dynamic model was first introduced in Skantze and Ilic (2001).
The model captures the basic nature of demand and supply including uncertainties, demand growth, and conditional capacity expansion. The analysis does not intend to forecast what will happen in particular markets, but it indeed provides a guideline to assess certain market setups that might lead to a desirable capacity investment dynamics

We compare an installed capacity market (ICAP) to a futures (forward) market, and emphasize the essential role of futures (forward) markets in providing crucial information for long-term investments that leads to sufficient supply and reserve margin. It is found that having market-based decisions by both supply and demand in response to sufficiently rich market signals would result in workable electricity markets, both short and long term.

2. LONG-TERM DYNAMIC MODELS OF DEMAND AND SUPPLY

To start with, we view an electricity market as a dynamic system. This system may include only spot markets, spot and ICAP markets (such as the New England market), or spot and futures markets (such as the Pennsylvania-Jersey-Maryland (PJM) and the California markets). The dynamic interactions within a full-blown market including spot, ICAP, and futures markets are presented in Figure 2.1.

Figure 2.1 Electricity Market as a Dynamic System



The monthly stochastic spot price model (Skantze and Ilic (2001)) captures the dynamics except demand elasticity (shaded area in Figure 2.1). Based on this model, monthly spot prices are represented as

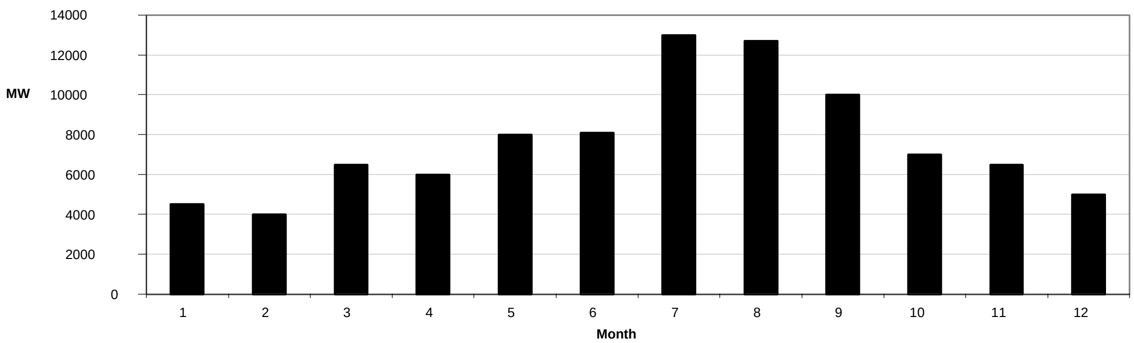
$$S_m = \exp(a \cdot L_m - b_m) \qquad \text{(Equation 2.1)}$$

with the monthly stochastic demand process (L_m), being an exogenous input described by:

$$L_m = \mu_m^L + \delta_m^L \qquad \text{(Equation 2.2)}$$
$$\delta_{m+1}^L - \delta_m^L = \kappa_m + \sigma_m^L \cdot z_m^L \qquad \text{(Equation 2.3)}$$

Here μ_m^L captures the seasonal behavior of load. In this study, we model μ_m^L using two approaches. The first approach assumes that μ_m^L to be a constant. The second approach assumes that μ_m^L varies over time as shown in Figure 2.2.

Figure 2.2 Initial Averaged Seasonal Demand



The state δ_m^L represents the long-term uncertainty in load, which grows stochastically with a drift κ, and volatility σ_m^L. z_m^L is a random variable with zero mean and variance equal to one. Note that this demand does not capture price elasticity nor the effect of long-term energy conservation policies.

Supply dynamics is, without an effect of an ICAP market (discarding the dotted lines in Figure 2.1), determined by the investors' feedback decision to invest and is described by:

$$b_m = \mu_m^b + \delta_m^b \qquad \text{(Equation 2.4)}$$
$$\delta_{m+1}^b - \delta_m^b = G \cdot \max(D_{m-\tau,m} - I, 0) + \sigma_m^b \cdot z_m^b \qquad \text{(Equation 2.5)}$$

Here μ_m^b reflects the initial capacity in the market (as an external driver). The state δ_m^b represents monthly supply dynamics, directly affected through the new investments $G \cdot \max(D_{m-\tau,m} - I, 0)$, and by the volatility σ_m^b (which reflects uncertainty in supply, but not limited to, outages and strategic behaviors). z_m^b represents a random variable with zero mean and variance equal to one. The parameter G determines the rate of investment in response to an investment signal, this is investor's control law. A decision variable $D_{m-t,m}$ can be arbitrary depending on which information is available, and is also dependent on the investors' choices. The details of deriving a decision variable $D_{m-\tau,m}$ will be described below, and are a function of market design and available information. The delay between the time when investment decision is made and a new power plant becomes operational[2], is accounted for through a delay parameter τ. An index I represents the expected return, averaged over the power plant life and technology, and it reflects the averaged marginal cost of running the new units, together with the installation cost.

[2] See Skantze and Ilic (2001) for more details about a parameter τ.

Total supply capacity C_m is calculated from:

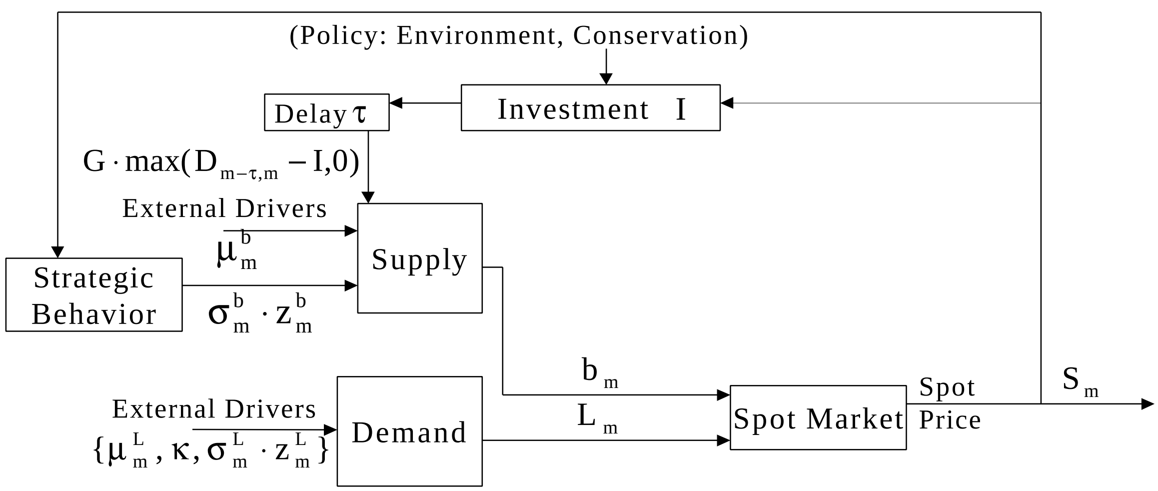
$$C_{m+1} = C_m + \frac{\delta^b_{m+1} - \delta^b_m}{a} = C_m + \frac{G}{a} \cdot (\max(D_{m-\tau,m} - I,0) + \sigma^b_m \cdot z^b_m) \qquad \text{(Equation 2.6)}$$

where C_0 is the initial capacity at time 0. C_m and b_m are directly proportional.
The reserve margin is then equal to:

$$R_m = C_m - L_m \qquad \text{(Equation 2.7)}$$

Therefore, a diagram representing the dynamics in Equations (2.1)-(2.7) of direct interest in this paper is derived by modifying the market general diagram in Figure 2.1 and is shown in Figure 2.3.

Figure 2.3 Long-term Dynamics of Demand and Supply



The investment generally affects the spot price dynamics once the new capacity is completely installed. As presented earlier in Equations (2.1)-(2.7), the monthly stochastic price process observes dynamics of spot prices at an aggregated level. New investment added to the market is captured through $G \cdot \max(D_{m-\tau,m} - I,0)$, in which an Index I reflects the minimal required return (the least expensive) of a unit that could be invested. A decision variable $D_{m-\tau,m}$ is obtained either using historic prices and/or futures prices, namely backward-looking and forward-looking investment schemes, respectively. In some markets, besides spot prices the ICAP prices are also available. In what follows, we carry an analysis of the effect of information used to determine an investment decision and its implications on market design.

3. ROLE OF FUTURES MARKETS

As presented in Skantze and Ilic (2001), a backward looking investment scheme, based on historic spot prices results in cyclical characteristics of monthly spot prices due to over-investment and under-investment. The investment decision in the backward looking scheme with time delay τ follows this formulation (Skantze and Ilic (2001):

$$D_{m-\tau,m} = \frac{1}{12} \cdot \sum_{j=1}^{12} S_{m-\tau-j} \qquad \text{(Equation 3.1)}$$

The dynamics of the state variable δ^b_m is described by:

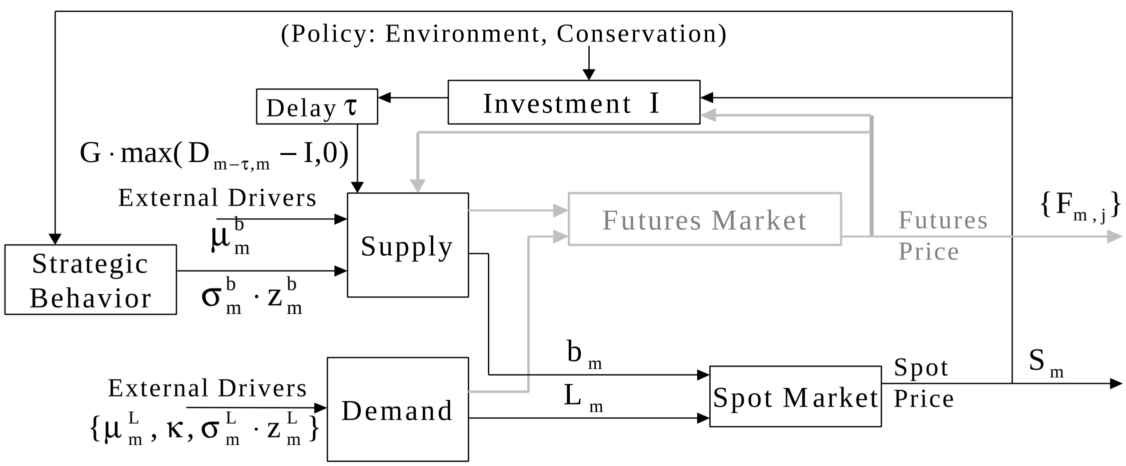
$$\delta^b_{m+1} - \delta^b_m = G \cdot \max(\frac{1}{12} \cdot \sum_{j=1}^{12} S_{m-\tau-j} - I, 0) + \sigma^b_m \cdot z^b_m \qquad \text{(Equation 3.2)}$$

In this paper, we extend the study to capture a forward looking investment scheme. It is assumed that a set of futures prices (F_m) \$/MW (with the duration of trading equal to P months), resulting from futures contracts for delivering electric power from month ($m+1$) to month ($m+P$), is available at the beginning of each month m (See Appendix for a basic method to simulate the futures prices), as

$$F_m = \{F_{m,m+1}, F_{m,m+2}, \ldots, F_{m,m+P}\} \qquad \text{(Equation 3.3)}$$

This is similar to adding a futures market to the diagram in Figure 2.2, as shown in Figure 3.1.

Figure 3.1 Long-term Price Dynamics in a Futures Market



Forward-looking Investment Dynamics

We assume that a (monthly) futures price with maturity in month ($m+\tau$) is an expected value of the monthly spot price of month ($m+\tau$):

$$F_{m,m+\tau} = E_m(S_{m+\tau}) \qquad \text{(Equation 3.4)}$$

In a forward-looking scheme, a decision variable $D_{m-\tau,m}$ is determined by the futures prices. Currently, futures contracts traded on NYMEX have the trading duration of 18 months. Installing a generator could take shorter or longer than the futures trading period. To capture the effect of the delay between the time when investment decisions are made and the time when the new generator is operating, one should consider two possible scenarios:

1. The trading duration of futures prices is longer than the time delay ($P > \tau$):

For this case, one possible way to determine the decision variable $D_{m-\tau,m}$ is to use the entire set of available futures prices, but put more weights on the futures prices of the months beyond τ, because these prices directly affect revenues of the new generators. The decision to invest influences the state variable δ^b_m after

τ months. Therefore, at the current month m, an effective decision variable is equal to $D_{m,m+\tau}$. We propose to use the following formula:

$$D_{m,m+\tau} = \frac{1}{P+1} \cdot \left(\frac{P-\tau}{\tau+1} \left(\sum_{j=1}^{\mu+1} F_{m,j} \right) + \frac{\tau+1}{P-\tau} \left(\sum_{j=\min(\tau+2,P)}^{P} F_{m,j} \right) \right) \qquad \text{(Equation 3.5)}$$

2. The trading duration of futures prices is not longer than the time delay ($P \le \tau$):

For this case future information obtained from the market does not contain the conditions when new units are actually going to operate. We propose to use the following formula:

$$D_{m,m+\tau} = \frac{1}{P} \cdot \sum_{j=m+1}^{m+P} F_{m,m+j} \qquad \text{(Equation 3.6)}$$

The initial conditions for all simulations chosen are:

a) Initial capacity (C_0) is set to 130% of initial demand, which is equal to μ_0^L. This reflects that the market starts with sufficient reserve margin (118% for the ICAP requirement in some markets[3]).
b) An Index I is set equal to 150 for the constant μ_m^L; it is equal to 60 for the μ_m^L shown in Figure 2.2.
c) The duration P of futures prices is 12 periods (months) for the constant μ_m^L; it is equal to 18 for the μ_m^L shown in Figure 2.2.
d) The investment rate G is equal to 0.001.

4. SIMULATIONS AND ANALYSIS

4.1 Spot Price Dynamics of Forward-looking and Backward-looking Investment Schemes

By using simulations, we analyze price dynamics obtained from backward-looking investment and forward-looking investment schemes for several choices of the delay, investment parameter τ and the trading duration of futures prices (P), assuming the same load dynamics.

Simulation Methods: At any month m

a) Demand L_m is calculated using Equations (2.2)-(2.3), and $z_m^L = \text{randn}(1)$ (MATLAB).
b) A set of futures prices $F_m = \{F_{m,m+1}, F_{m,m+2}, \ldots, F_{m,m+P}\}$ is known. To calculate these futures prices we follow the Monte Carlo approach (See Appendix). Note that we keep an investment decision $G \cdot \max(D_{m-\tau,m} - I, 0)$ from prior periods, which is added to the spot price dynamics at the current month m.
c) Spot price at month m is calculated using Equations (2.1)-(2.5), and $z_m^b = \text{randn}(1)$.
d) A decision variable $D_{m,m+\tau}$ is calculated using either Equation (3.5) or (3.6) depending on the time delay. A new investment is equal to $G \cdot \max(D_{m,m+\tau} - I, 0)$. This affects the spot price dynamics beginning at month ($m+\tau$) or τ months later.
e) Capacity of each month is obtained using Equation 2.6.

[3] Such as that required in the New York Power Pool.

Simulation with no time delay

Under the no investment delay assumption, forward-looking and backward-looking investment schemes yield similar outcomes as shown in Figures (4.1)- (4.4). Both investment schemes result in satisfactory reserve margin. However, this assumption is unrealistic for the case of adding new capacity by installing new generators. On the other hand, it is feasible when importing power from neighboring areas.

Figure 4.1 Monthly Spot Prices under no Investment Delay Assumption

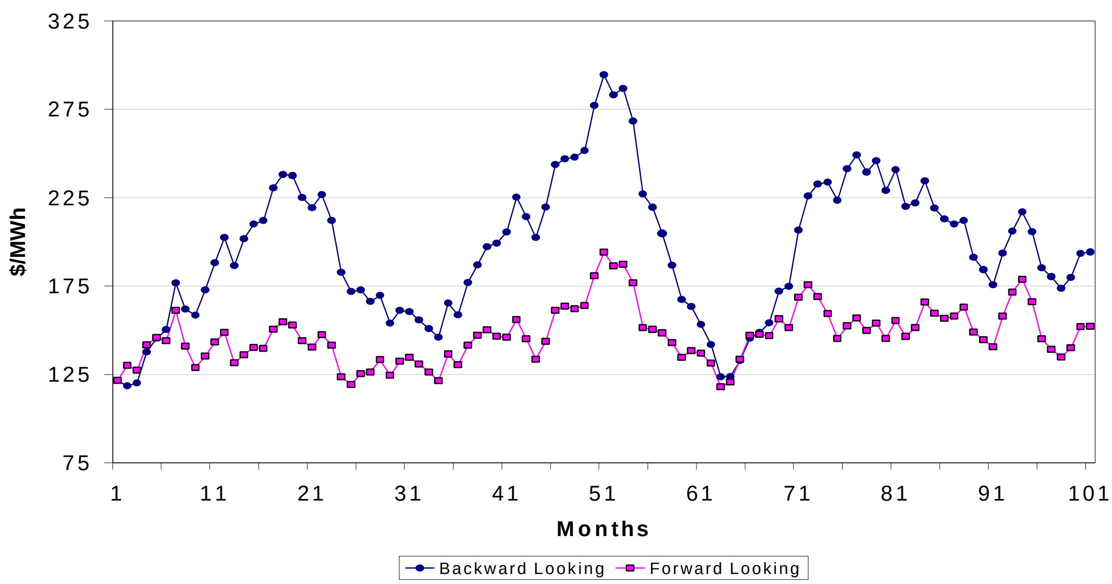


Figure 4.2 Supply Capacity and Demand under no Delay Assumption

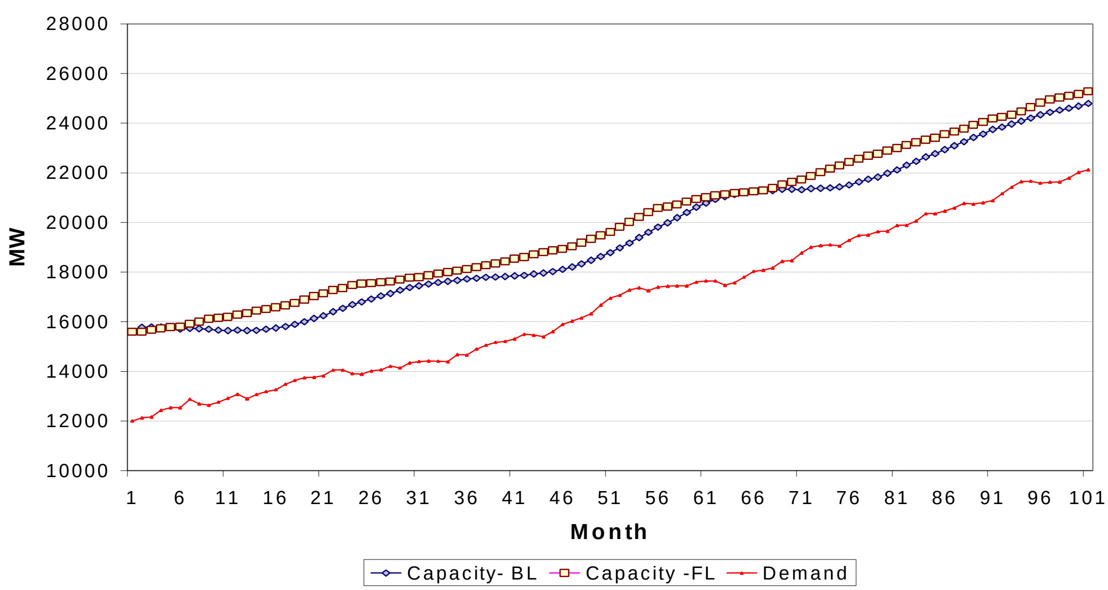


Figure 4.3 Monthly Spot Prices under no Investment Delay Assumption with Seasonal Demand

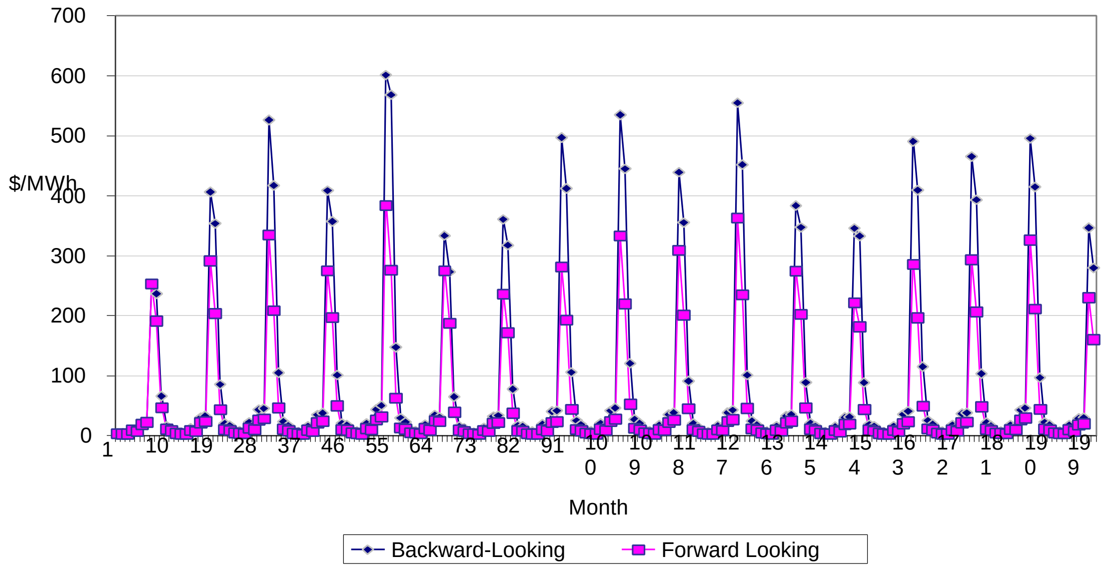
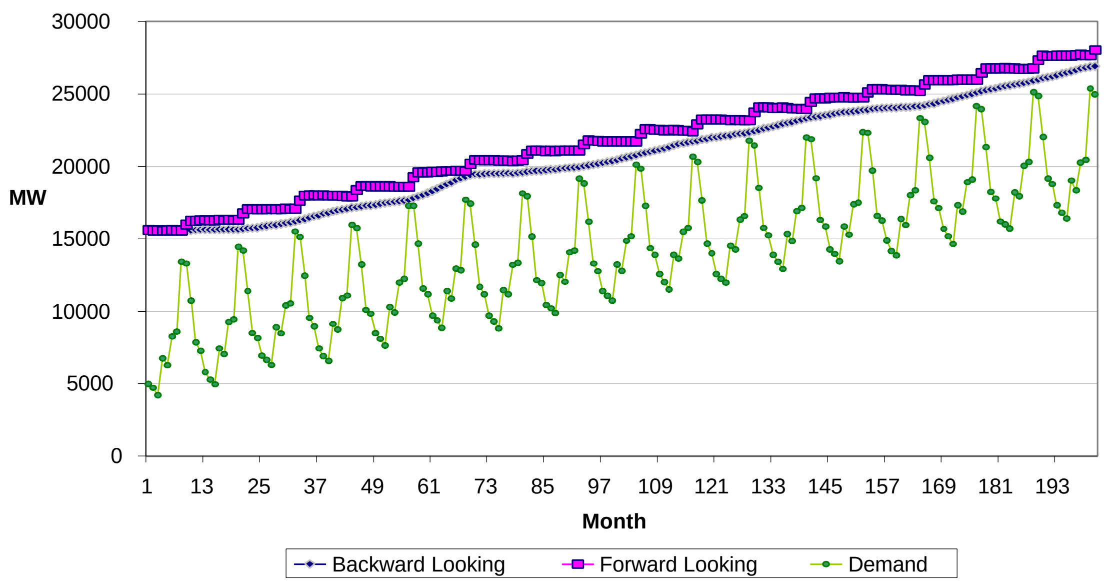


Figure 4.4 Supply Capacity and Demand under no Delay Assumption with Season Demand



In the backward-looking scheme, the historic prices are used to determine the investment decision variable. This tends to create an under-investment condition since increased demand in the future is neglected. On the other hand, in the forward-looking scheme the future load growth is accounted for. Note that the cyclical behavior of price dynamics as a result of the backward-looking scheme can be observed.

Simulation with an investment delay

We explore the effect of time delay on price dynamics in two cases. The first case is when the investment delay τ is shorter than the trading duration of futures P. The simulation results are shown in Figures (4.5)-(4.8). The other case is when the investment delay τ is longer than the trading duration of futures P. The simulation results are shown in Figures (4.9)- (4.12).

Figure 4.5 Monthly Spot Prices: with 6-period Time Delay $\tau < P$

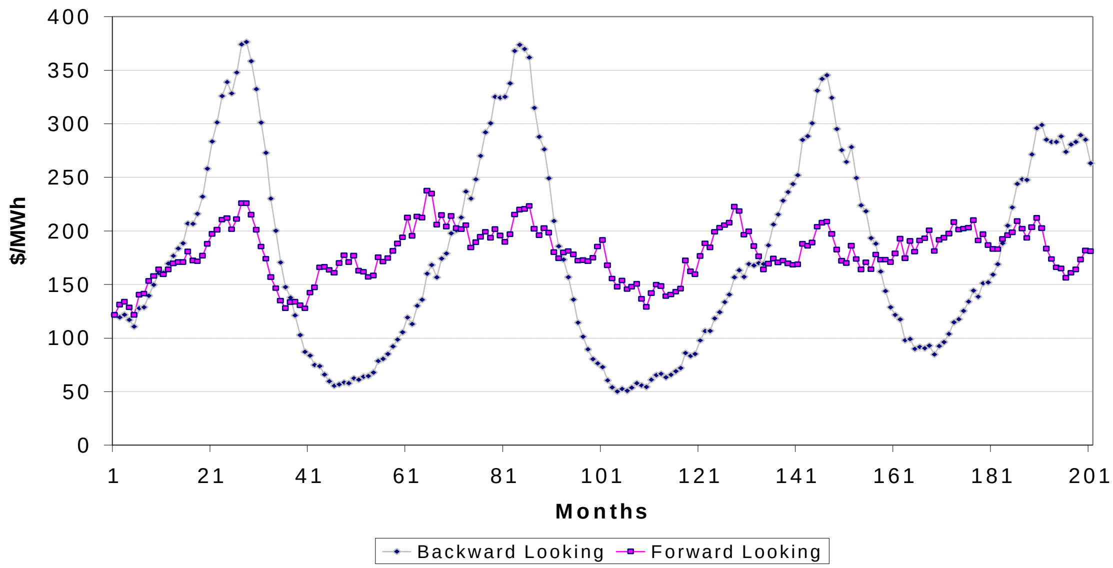


Figure 4.6 Available Supply Capacity and Demand: with 6-period Time Delay $\tau < P$

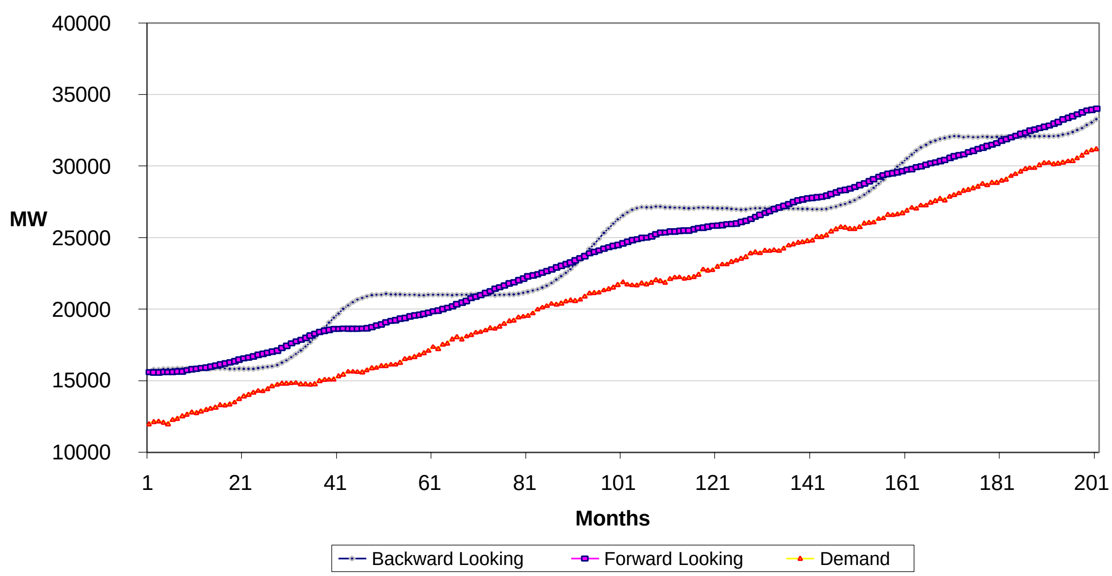


Figure 4.7 Monthly Spot Prices: with Seasonal Demand and 12-period Time Delay $\tau < P$

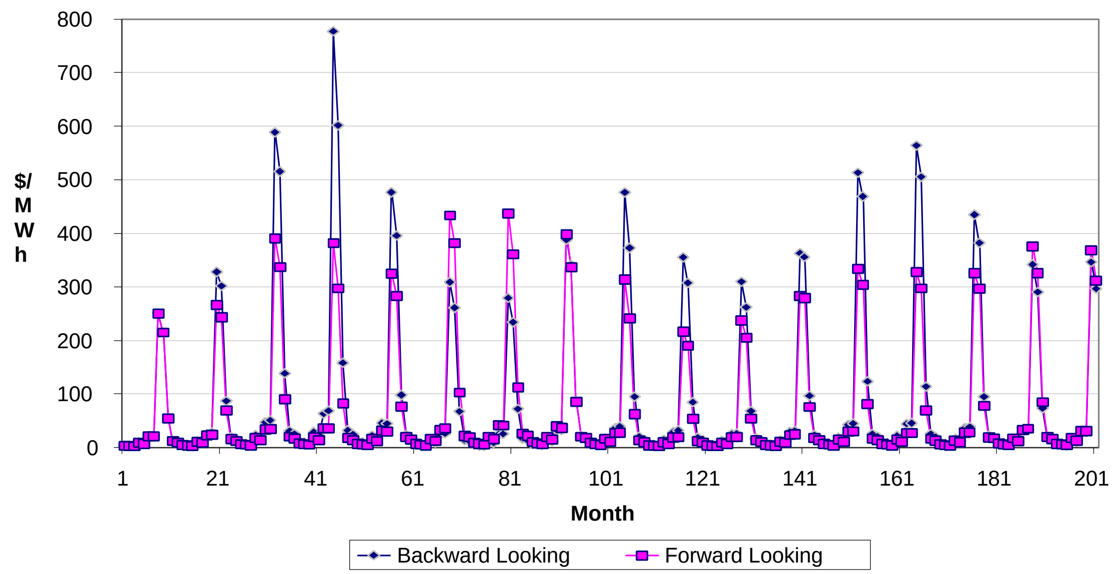


Figure 4.8 Available Supply Capacity and Demand: with Seasonal Demand 12-period Time Delay $\tau < P$

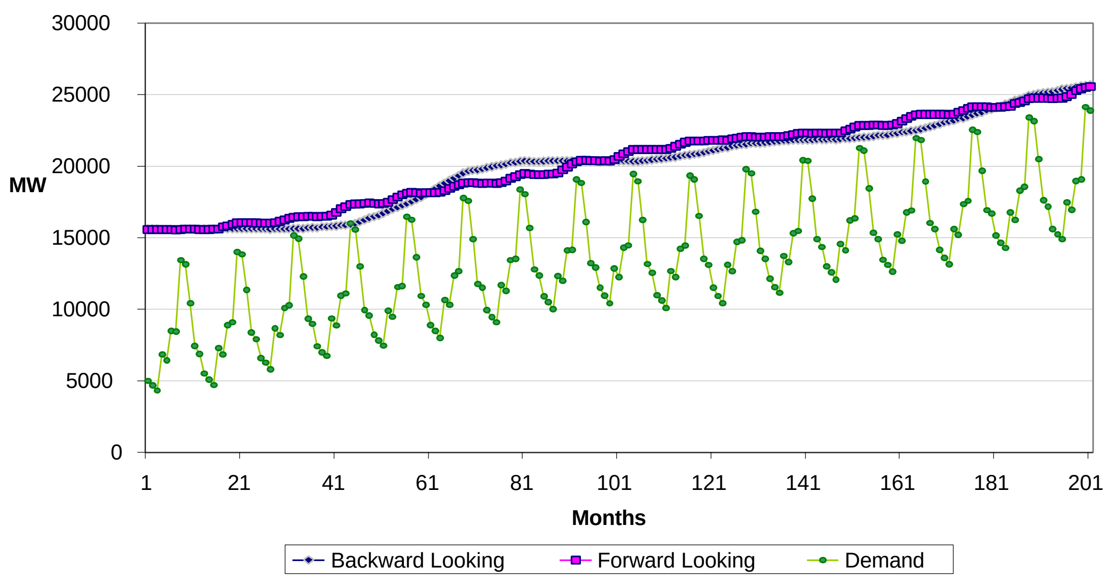


Figure 4.9 Monthly Spot Prices: with 14-period Time Delay $\tau \geq P$

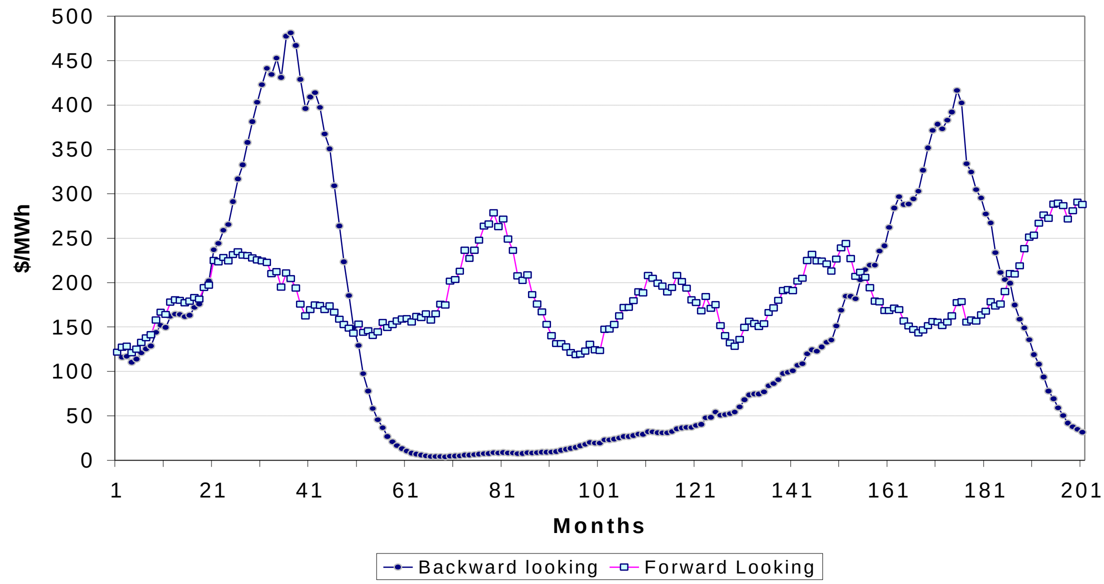


Figure 4.10 Supply Capacity and Demand: with 14-period Time Delay $\tau \geq P$

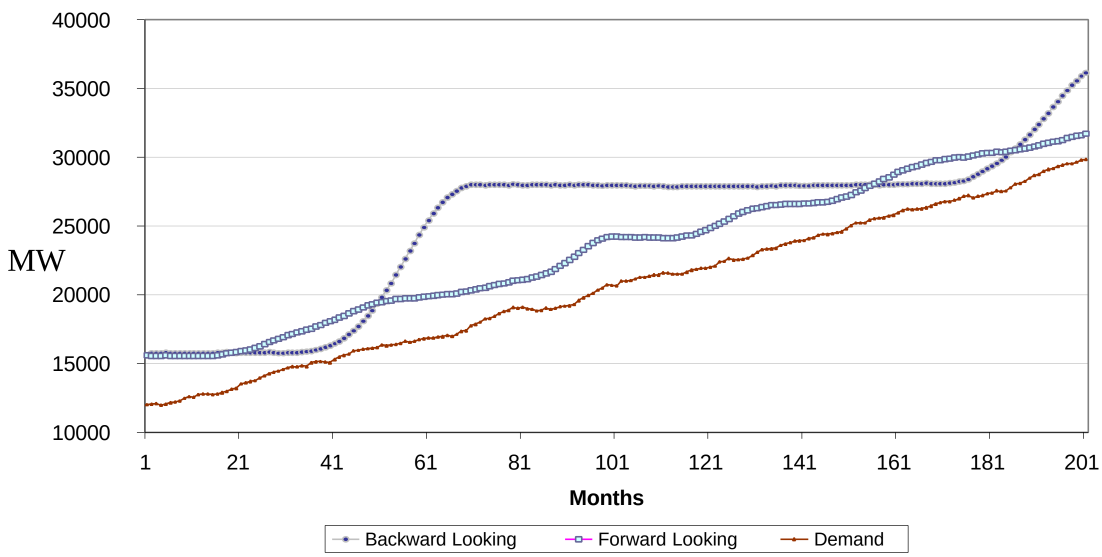


Figure 4.11 Monthly Spot Prices: with Seasonal Demand and 24-period Time Delay $\tau \geq P$

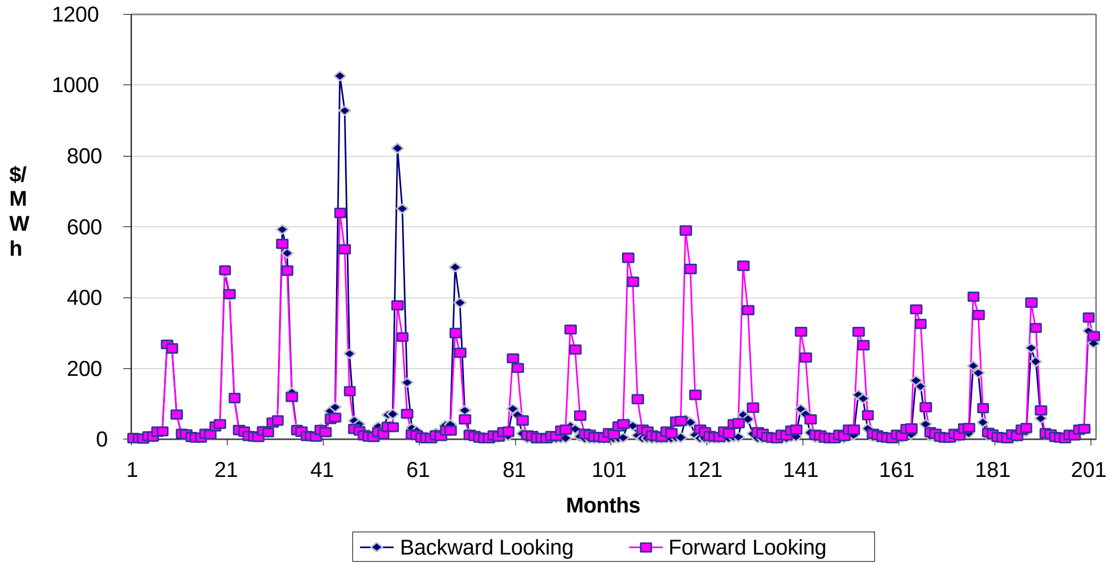


Figure 4.12 Supply Capacity and Demand: with Seasonal Demand and 24-period Time Delay $\tau \geq P$

One can observe from Figures (4.5)-(4.12) that when the backward-looking investment scheme is applied, over-investment and under-investment conditions are extreme. This characteristic is not obvious in the forward-looking scheme, where the reserve margin tends to be relatively smooth. The long delay in installing new generators causes a near supply deficiency condition and yields extremely high electricity prices.

Note that spot prices obtained from forward-looking scheme also display a cyclical characteristic when the time-delay of installation exceeds the duration of futures prices, i.e. $\tau > P$.

4.2 The Effect of an ICAP Market on Long-term Dynamics Investment

An installed capacity (ICAP) market is generally designed for ensuring adequate generation capacity when an equipment contingency occurs. ICAP market rules are often market specific.

a) The New York Power Pool (NYPP) ICAP Market:

In the NYPP, purchasing the required ICAP is held every six months including the summer and winter periods. The summer period starts from May to October, and the winter period starts from November to April. Demand for ICAP is set to be 118% of anticipated annual peak demand. All load-serving entities (LSE) are obliged to meet the ICAP requirement[4],

$$L_m^{ICAP} = 1.18 \times \max_h (L_h) \qquad \text{(Equation 4.1)}$$

b) The New England Power Pool (NEPOOL) ICAP market:

In the NEPOOL, purchasing the required ICAP is held every month.

In this study we wish to compare the resulting spot price dynamics in response to the ICAP prices (an ICAP-based investment scheme) to the resulting spot price dynamics in response to the forward-looking scheme. We assume that a set of ICAP prices is available at every month that ICAP purchasing is held (every $\overline{P}$ -month period).

$$S^{ICAP} = \{S_{m+1}^{ICAP}, \ldots, S_{m+\overline{P}}^{ICAP}\} \qquad \text{(Equation 4.2)}$$

Futures and ICAP Markets

Although, a futures market and an ICAP market are designed for trading generation capacity in advance, they are different in several aspects. Futures contracts are primarily based on financial valuations, while ICAP contracts are mainly intended for maintaining system reliability. Futures contracts bought or sold are either financial or physical (required delivery). An offer to purchase or sell a futures contract comes from any entity, such as marketers, a load serving entity, a generator owner, or a transmission provider, because the futures contracts are fundamentally used for hedging and speculating. One contract includes delivering specified power for at least one-month period. Volume of the contracts traded in the futures market is usually multiple times of demand in the spot market volume.

On the other hand, an ICAP contract is traded for availability of existing capacity during a specified period. In an ICAP market, the ICAP suppliers bid to sell their available capacity to the load serving entities with deficit of ICAP requirements. The demand for ICAP is directly related to the demand in the spot market. Note that if market power does exist, the ICAP suppliers are likely submit a strategic price to reap more profits (without attracting a new entry).

For investment purposes, an investor might find that ICAP prices would indicate nearly true demand and supply conditions, while futures markets might include information effects on demand and supply conditions together with hedging and speculation.

Setting ICAP Prices in Simulations

We consider two scenarios:

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[4] For more details regarding to the ICAP requirement is the NYPP, visit http://www.nyiso.com.

a) Demand for ICAP L_m^{ICAP} is bigger or equal to total available capacity C_m^{total}:

When $L_m^{ICAP} \geq C_m^{total}$, ICAP suppliers have absolute market power as shown in Visudhiphan and Ilic (2000). Since in this model demand and supply are aggregated, the condition in which the largest supplier can exert its absolute market power cannot be observed directly, except when $L_m^{ICAP} \geq C_m^{total}$. Therefore, if there is a supply scarcity in the ICAP market, the price of ICAP will be set to be (substantially) greater than zero. If investors base their decisions on the ICAP prices, one should consider two cases:

1) $S_m^{ICAP} = \exp(a \cdot L_m^{ICAP} - b_m)$ (Equation 4.3a)
2) $S_m^{ICAP} = \overline{S}$, i.e., $\overline{S} = 500$ (Equation 4.3b)

Note that if $\overline{S}$ is set too low, it would affect the long-term dynamics of investments similar to that of the low energy price cap as presented in Skantze and Ilic (2000). The inexpensive price deters new investments and creates deficiency in a supply.

b) Demand for ICAP less than total available capacity C_m^{total}:

When $L_m^{ICAP} < C_m^{total}$, no absolute market power condition exists (or it does exit, but it is not observable). All generators subject their capacity to the spot market. There is no opportunity cost for available capacity. Therefore, the ICAP price is set to be: $S_m^{ICAP} = 0$ (Equation 4.4)

The effect of ICAP Prices on Investment Dynamics

a) Investment Criteria

In this section, the role of the ICAP prices on investment dynamics is investigated. An average of observed ICAP prices in a given ICAP period is computed as an investment decision variable

$$D_{m,m+\tau} = \frac{1}{\overline{P}} \cdot \sum_{j=1}^{\overline{P}} S_{m+j}^{ICAP} \quad \text{(Equation 4.5)}$$

$\overline{P}$ is the trading duration of the ICAP (a 6-month period for the NYPP).

b) Simulations

The simulations show the effects of the ICAP-based investment scheme for various installation time delays on dynamics of investment. Since in our model, demand dynamics vary on a monthly basis, the demand for ICAP requirements is set to be:

$$L_m^{ICAP} = 1.18 \times L_m \quad \text{(Equation 4.6)}$$

In the following simulations, if there is an absolute market power condition, the ICAP price will be equal to

$$S_m^{ICAP} = \exp(a \cdot (1.18 L_m) - b_m) \quad \text{(Equation 4.7)}$$

ICAP is traded every six months. When there is no trade, an investment decision process ($G \cdot \max(D_{m-\tau,m} - I, 0)$) is idle. Therefore, capacity expansion is not smooth.

Simulation Methods: At any month m

a) Demand L_m is calculated using Equations (2.2)-(2.3), and $z_m^L = \mathrm{randn}(1)$ (MATLAB).
b) A set of ICAP prices $S^{ICAP} = \{S_{m+1}^{ICAP}, \ldots, S_{m+6}^{ICAP}\}$ is known in every period that ICAP purchasing is held ($\overline{P} = 6$ throughout the simulations). To calculate these ICAP prices we follow the Monte Carlo approach (Appendix). Note that we keep an investment decision $G \cdot \max(D_{m-\tau,m} - I, 0)$ from prior periods to calculate ICAP prices.
c) Spot price at month m is calculated using Equations (2.1)-(2.5), and $z_m^b = \mathrm{randn}(1)$.

d) A decision variable $D_{m,m+\tau}$ is calculated using Equation (4.5). A new investment is equal to $G \cdot \max(D_{m,m+\tau} - I, 0)$. This affects the spot price dynamics beginning at month $(m+\tau)$ or τ months later.

e) Capacity of each month is obtained using Equation (2.6).

Figure 4.13 Monthly Spot Prices: ICAP-based Investment Decisions with 14-period Time Delay

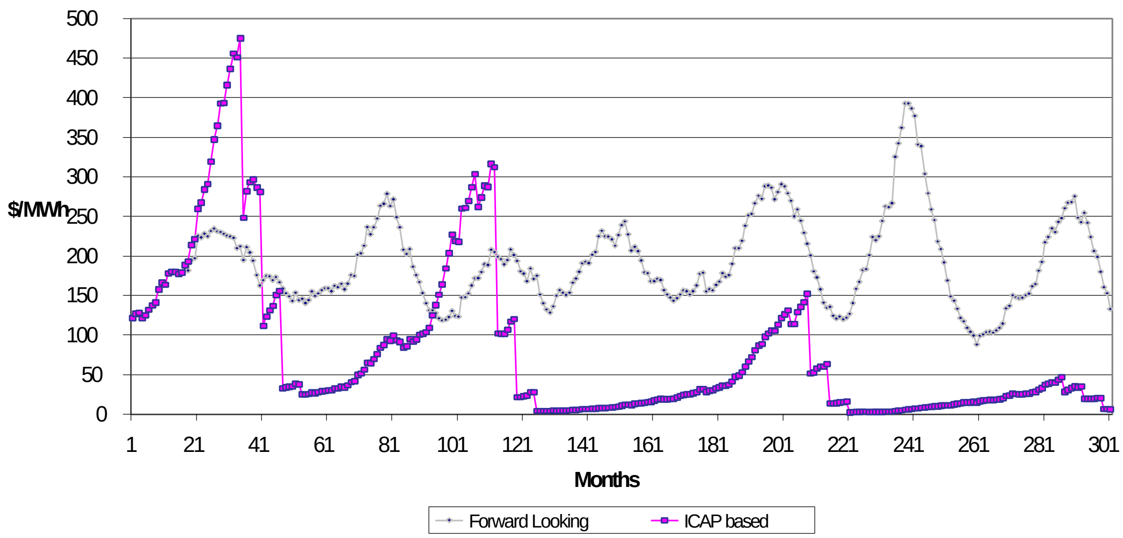


Figure 4.14 Supply Capacity and Demand: ICAP-based Investment Decisions with 14-period Time Delay

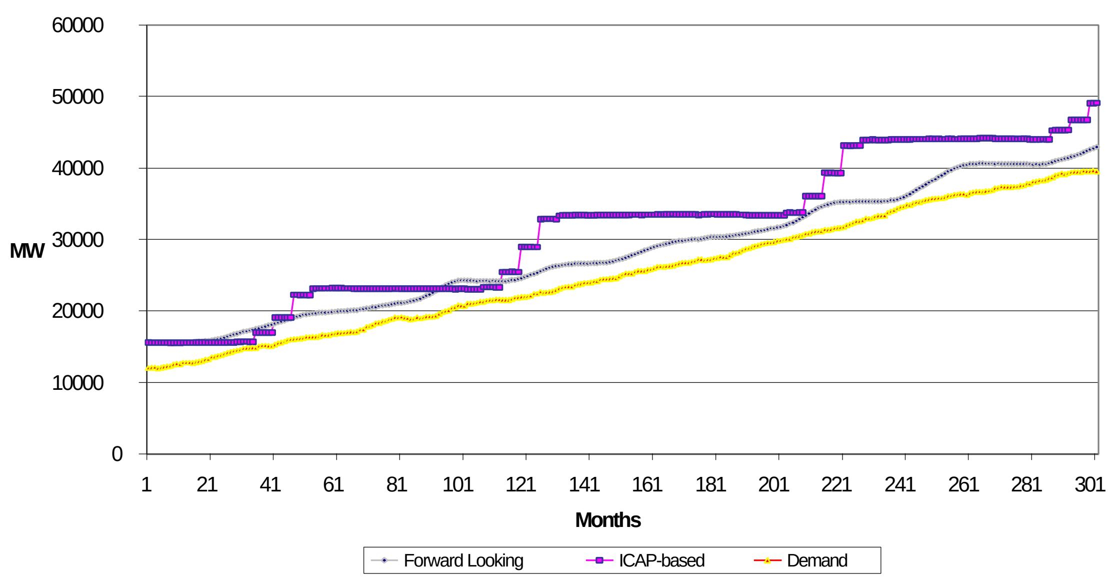


Figure 4.15 Monthly Spot Prices: ICAP-based Investment Decisions with 6-period Time Delay

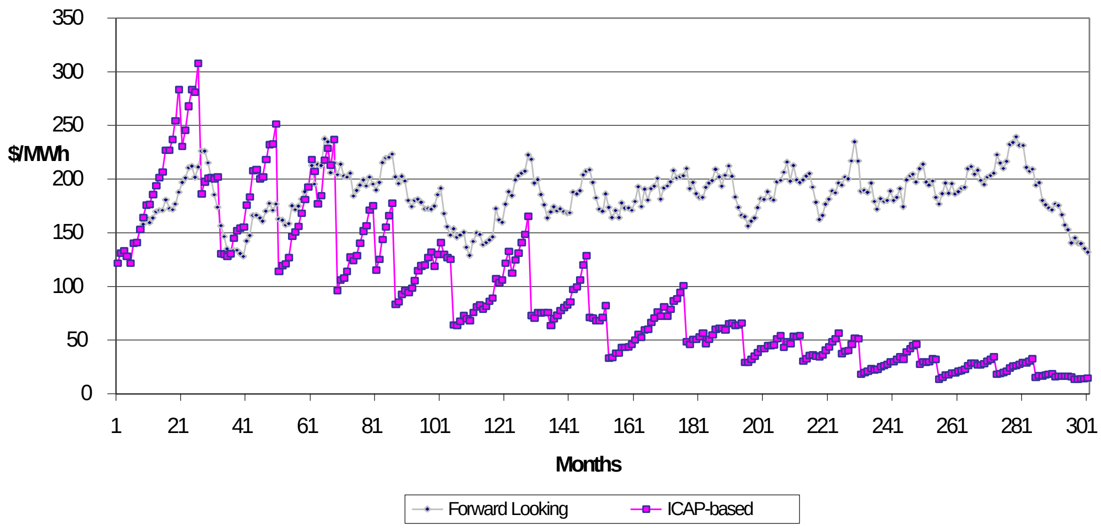


Figure 4.16 Supply Capacity and Demand: ICAP-based Investment Decisions with 14-period Time Delay

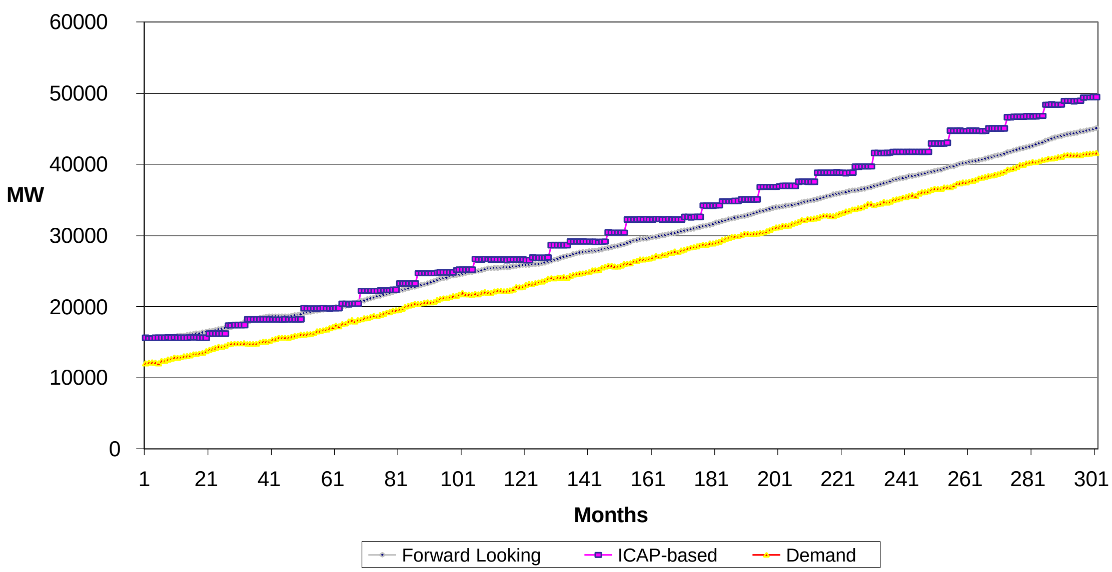


Figure 4.17 Monthly Spot Prices: ICAP-based Investment Decisions with Seasonal Demand and 24-period Time Delay

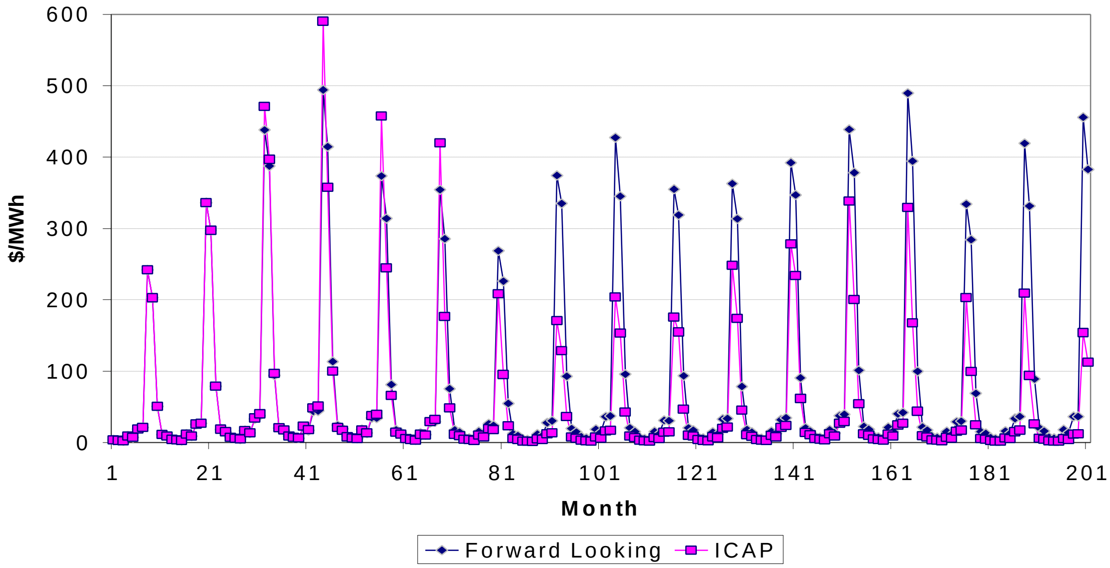
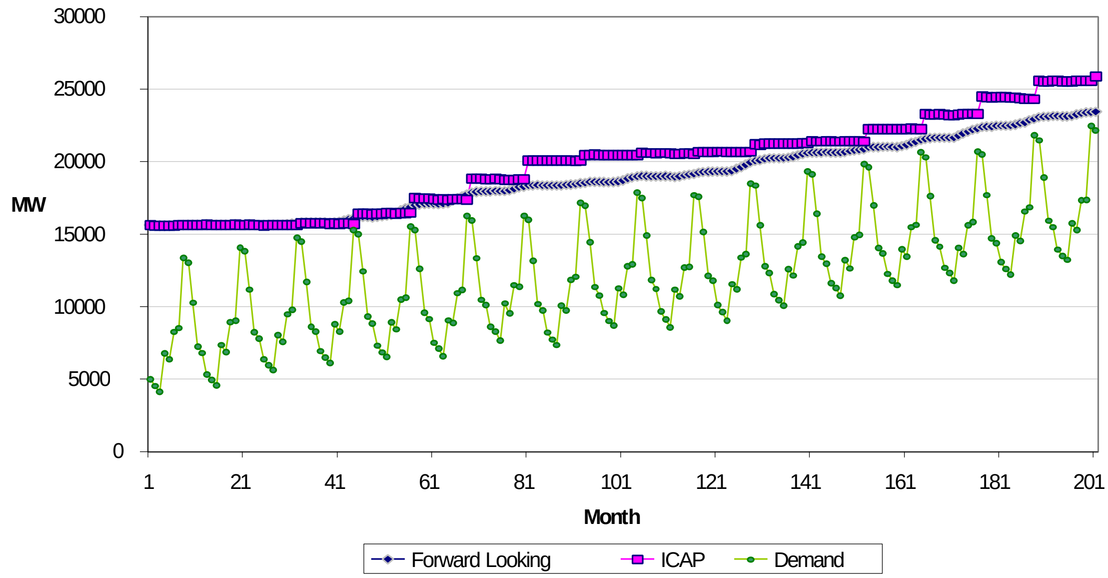


Figure 4.18 Supply Capacity and Demand: ICAP-based Investment Decisions with Seasonal Demand and 24-period Time Delay



The ICAP requirement equaling 118% of the peak demand causes successive investments in capacity expansion as demand is growing. One would anticipate high ICAP prices in order to maintain increasing required capacity. Time delay affects market prices in the ICAP-based investment decisions, the same way as those investments are determined from futures prices based on the forward looking scheme.

This model fails to capture that the units added to the market in response to increasing ICAP demand are not profitable in the energy market. Due to oversupply, energy prices are driven down. The question remains as of how to set the right index for an ICAP-based case in which monthly payment is accounted; and if in real practice, the payment from providing ICAP alone would be sufficient for generators to stay in business.

5 CONCLUSIONS

This paper reports on preliminary modeling and simulations of the long-term electricity price dynamics. We first introduced the problem broadly, and supported it by a general block diagram in which many factors affect the long-term electricity prices. Next, the paper focuses on the particular problem of investment dynamics and the rate at which the investment decisions evolve. It is shown that the investments are function of the type of electricity markets in place. For spot markets, projections concerning investments can only be made using historic data. This generally results in considerable delays and under-investments. In this paper this is demonstrated using a backward-looking scheme. In contrast, the availability of futures market provides a timely information on the potential value of the investment of interest and, therefore, generally leads to smaller supply/demand imbalances. Finally, the effect of ICAP market signals for investment decisions is shown to be rather distorting and misleading with regard to the value of investment-related decisions. This paper as a whole, views the markets as a dynamic process with various feed forward and feedback signals interacting with the basic supply/demand drivers. Much more remains to be done to include variety of other effects, such as the dynamics of strategic bidding and locational aspects of the market. Authors are currently pursuing this work.

6 APPENDIX

Monte Carlo Simulation Method for Forward-looking Dynamic Investments

In this paper futures prices are simulated assuming that $F_{m,m+j} = E_m(S_{m+j})$. In the actual market, these are observable. To simulate futures prices using spot market data, a spot price from the previous period (m-1) is taken as an initial condition for the simulated futures prices observed at the current period (m). $F_{m,m+j}$ is obtained by applying a Monte Carlo approach. Many sets (N) of possible spot prices over the duration of available futures prices P are simulated using the formula in Equations (2.1)-(2.5), i.e.

$$\left\{\begin{matrix} \hat{S}^1_{m+1}, \hat{S}^1_{m+2}, \ldots, \hat{S}^1_{m+P} \\ \vdots \\ \hat{S}^N_{m+1}, \hat{S}^N_{m+2}, \ldots, \hat{S}^N_{m+P} \end{matrix}\right\}$$

Futures prices observed at time m are then calculated as:

$$\hat{F}_{m,m+j} = \frac{1}{N}\sum_{i=1}^{N} \hat{S}^i_{m+j}, \ \forall j \in [1, P]$$

Spot prices in a simulated path i include new capacity anticipated to operate as a result of investments made in earlier periods, i.e.

$$\delta_{m+1+j} - \delta_{m+j} = G \cdot \max(D_{m-\mu+j,m+j} - I, 0) + \sigma_{m+j} \cdot z_{m+j}$$

One can think of $G \cdot \max(D_{m-\mu+j,m+j} - I, 0)$ as additional capacity, which is recorded when the investors make their "public" decision at time ($m - \mu + j$). In this paper, a matrix containing new investment information with time delay is introduced and it is referred to as a new-capacity matrix:

$$
\begin{array}{l}
m=0 \\ \vdots \\ m=\tau \\ \vdots
\end{array}
\Rightarrow
\left\{
\begin{array}{cccccccc}
0 & 0 & \cdots & G\cdot\max(D_{0,\tau}-I,0) & \cdots & 0 & 0 & 0 \\
\vdots & & & \vdots & & & & \\
G\cdot\max(D_{0,\tau}-I,0) & G\cdot\max(D_{1,\tau+1}-I,0) & & G\cdot\max(D_{\tau,\tau+1}-I,0) & & \cdots & & \\
\vdots & & & \vdots & & 0 & 0 & 0
\end{array}
\right\}
$$

After $\hat{F}_{m,m+j}$ is obtained, at the end of the current period (m), investors decide to build new units if the decision variable $D_{m,m+\tau}(\{\hat{F}_{m,m+j}\})$ is greater than the index (I). If this condition is satisfied, the new investment will be installed and ready to operate in τ periods later. Additionally, this decision is recorded for the calculation of futures prices in later periods (from period m+1 on).

Monte Carlo Simulation Method for Calculating ICAP Prices

How should ICAP requirements and ICAP prices at time m be determined? Demand from the previous period (m-1) is taken as an initial condition for the simulated requirements for ICAP observed at the current period (m). The ICAP requirement set to 118% of monthly demand L_{m+j} is obtained by applying a Monte Carlo approach. Many sets (N) of possible demand over the duration of ICAP purchasing period are simulated using Equation (2.2)-(2.3), i.e.

$$
\begin{Bmatrix}
\hat{L}^1_{m+1}, \hat{L}^1_{m+2}, \ldots, \hat{L}^1_{m+\bar{P}} \\
\vdots \\
\hat{L}^N_{m+1}, \hat{L}^N_{m+2}, \ldots, \hat{L}^N_{m+\bar{P}}
\end{Bmatrix}
\Rightarrow
\begin{Bmatrix}
\hat{L}^{ICAP,1}_{m+1}, \hat{L}^{ICAP,1}_{m+2}, \ldots, \hat{L}^{ICAP,1}_{m+\bar{P}} \\
\vdots \\
\hat{L}^{ICAP,N}_{m+1}, \hat{L}^{ICAP,N}_{m+2}, \ldots, \hat{L}^{ICAP,N}_{m+\bar{P}}
\end{Bmatrix}
$$

The ICAP requirement observed at time m is calculated as:

$$\hat{L}^{ICAP}_{m+j} = \frac{1}{N}\sum_{i=1}^{N}\hat{L}^{ICAP,i}_{m+j}, \ \forall j \in [1,\bar{P}]$$

Similarly, we also apply a Monte Carlo simulation to determine the state variable δ^b_m during the simulated ICAP requirement duration ($\bar{P}$) and subsequently to determine available capacity C_m from δ^b_m using Equation 2.6. Note that to calculate δ^b_m, $G\cdot\max(D_{m-\tau+j,m+j}-I,0)$ must be included through:

$$\delta_{m+1+j} - \delta_{m+j} = G\cdot\max(D_{m-\mu+j,m+j}-I,0) + \sigma_{m+j}\cdot z_{m+j}$$

$$
\begin{Bmatrix}
\hat{\delta}^1_{m+1}, \hat{\delta}^1_{m+2}, \ldots, \hat{\delta}^1_{m+\bar{P}} \\
\vdots \\
\hat{\delta}^N_{m+1}, \hat{\delta}^N_{m+2}, \ldots, \hat{\delta}^N_{m+\bar{P}}
\end{Bmatrix}
\Rightarrow
\begin{Bmatrix}
\hat{C}^1_{m+1}, \hat{C}^1_{m+2}, \ldots, \hat{C}^1_{m+\bar{P}} \\
\vdots \\
\hat{C}^N_{m+1}, \hat{C}^N_{m+2}, \ldots, \hat{C}^N_{m+\bar{P}}
\end{Bmatrix}
$$

Available capacity observed at time m is calculated as:

$$\hat{C}_{m+j} = \frac{1}{N}\sum_{i=1}^{N}\hat{C}^i_{m+j}, \ \forall j \in [1,\bar{P}]$$

and the ICAP prices are determined using Equations (4.3)-(4.4).

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