An Evolutionary Analysis of Investment in Electricity Markets

Manuel L. Costa

CEMPRE, Faculdade de Economia do Porto, Portugal, mlcosta@fep.up.pt

Fernando S. Oliveira

Warwick Business School, UK, fernando.oliveira@wbs.ac.uk

Abstract: We developed an evolutionary model of investment in liberalized electricity markets, which aims to capture the long-term implications of short-term policies by simulating how price caps, reserve margins and capacity payments influence the evolution of market structure. We show that: - the impact of an investment on market price depends on the technology used; - capacity payments can give the correct incentives for investment; - price caps and price uncertainty have a non-linear relationship with investment; - in the long-run electricity markets tend to be short of capacity, and consequently regulation is a necessary condition for reliability.

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1. Introduction

Electricity markets are being liberalised and open to private competition in several countries. This liberalisation process has been difficult (with several changes on market rules), painful (with extremely high price spikes - California - and power cuts – USA, Europe and Brazil), but also successful (with several countries reporting lower electricity prices, such as in England & Wales).

Moreover, electricity markets are quite complex as the interactions between demand and supply are subject to several technical constraints. One of these technicalities is that generators cannot store electricity which is generated on real-time. Furthermore, due to the vital importance of electricity for the economy and wealth of nations, and due to the oligopolistic structure of these markets, together with a low elasticity of demand, these markets are highly regulated.

As has been shown, in liberalized electricity markets short term policies may have long-term impacts on the reshaping of market structure through mergers, acquisitions, investment and divestures (Cox, 1999). Electricity companies may use mergers, acquisitions, investment (or divestment) to adapt to the new environment or to gain market power. Furthermore, the logic behind investment (divestment) in electricity markets changed dramatically with the liberalization process (Larsen and Bunn, 1999). The new industry is characterized by: - unstable and volatile prices; - the presence of new shareholders with diverse objectives; - regulatory uncertainty; - Information opacity. Moreover, at a corporate level we have: - a focus on shareholder value; - uncertainty and limited information. In fact, regulatory choices may have important impacts on shareholder value.

Therefore, within the new liberalized markets, and due to the decentralization of the long-term decisions, the investment problem became an important issue. The privatized market presents an increased risk due to price and demand uncertainty and due to competition (the investment projects are private). Consequently, there is a need to explain how electricity companies and these markets evolve in the short and long-term, and to explain the impact of uncertainty on the value of electricity plants.

We present an evolutionary model of investment in electricity markets aiming to analyze the following research questions: What is the impact of demand cycles on market structure and long-term behavior? What is the interaction between price caps, reserve margins, duration of demand and the level of investment? What is the implication of electricity price uncertainty on investment? Can markets invest enough capacity to ensure the long run security of the market?

Next, this paper provides a background towards modeling of electricity markets. Then in Section 3 we present the model used to capture the investment and pricing behavior and in Section 4 we illustrate the workings of the model for several scenarios for price caps, reserve margins and capacity payments. Section 5 concludes the paper.

2. Background to Electricity Markets Modeling

An issue that has been modeled in electricity markets is the market clearing mechanism and its short term performance. The short-term modeling of electricity markets using agent-based models has been the topic of Bower and Bunn (2001) who study discriminatory pricing in bilateral electricity markets; Bunn and Oliveira (2001) who developed a simulation platform to analyze market clearing in the England & Wales NETA; Nicolaisen, Petrov and Tesfatsion (2001) who developed an agent-based model of an electricity market using a single-call market.

The main concern with this short term analysis is the possibility of abuse of market power. High price caps allow a supplier to withhold a greater percentage of its capacity and still make a profit due to the resulting increase in market price. Additionally, the ratio of the duration of maximum prices with and without the exercise of market power is greater for low-duration price spikes. Because high price caps must be designed to produce low-duration price spikes, high price spikes exhibit a greater percentage increase in duration as a result of an equal level of withholding.

Moreover, a second important issue in electricity markets is reliability. If the price spikes are large enough, they induce the investment that provides the generating capacity necessary for a reliable system, which has the ability to adapt to sudden disturbances in the network and has enough capacity to ensure security almost all of the time. Therefore, installed capacity is the fundamental determinant of reliability. The greater the installed capacity, the smaller the value of lost load, and the greater the cost of serving load. This cost trade-off determines the optimal value of investment.

The issue of investment in electricity markets has been recently addressed by several differnt approaches. Skantze et al. (2000) model investment in the liberalized electricity markets by using a two stage dynamic programming model (with stochastic prices for both electricity and fuel). Within the same topic, Visudhiphan et al. (2001) model investment dynamics in a system with a spot and a futures market, analysing how price information affects long-term supply, demand and price evolution. In both these papers, demand and generation evolution is assumed exogenous, and market structure is not considered a determinant of generation behaviour and price evolution.

Furthermore, Pineau and Murto (2003) modelled investment in electricity markets by using a stochastic Cournot oligopoly game of the Finnish electricity market. Within this

model, they capture demand as a stochastic process and define generation capacity as a function of players' strategies and stochastic elements. Further, generators can only invest in gas and coal plants (the period modelled was 10 years) and the market is segmented into baseload and peak demand. The alarming conclusion of this work is that the higher uncertainty in the liberalised electricity markets, when compared with the monopoly situation, and in the presence of big players, leads to lower investments and, in the long-run, may threaten system reliability and lead to high prices.

In all the above cited papers regulation is absent, and the market is modeled as if the players optimize their policies for a given pattern of price behavior, of behave as Cournot players. However, there are several regulatory policies such as price caps, reserve margins and capacity payments that can have a very important impact on both the short and long term behavior of the market. Before proceeding to modeling these policies, in Section 3, next we present a brief summary of their main characteristics.

The level of the price cap will determine the profitability of investing in peak plants (which only run during the times of the day with the highest demand) and the reliability of the system as a whole in the long-run. Therefore, it would seem that if this price cap is too low investing in peak plant will not be profitable. Moreover, the price cap on the spot market indirectly imposes a cap on the electricity price in the futures market, as no firm would buy at a higher price than this one. This price cap is also very important due to its long-term impacts. The price spike provides a scarcity rent for generators, and therefore must be high enough to allow peakers and baseload plants to cover their fixed costs from short-run profits.

Furthermore, the capacity payments may also influence investment (divestment) decisions. Exelby and Lucas (1993) examined the link between capacity payments and

capacity investment in the E&W Pool, showing that the capacity payments mechanism introduced incentives to reduce the capacity available in the system. Moreover, they reveal that the incumbent's optimum behavior was to adopt a quasimonopoly strategy, and that capacity payments were only an incentive for new entrants to invest.

Another instrument available to regulators is de imposition of reserve margins (capacity requirements). The capacity requirement bears a relatively clear and stable relationship to reliability. The requirement for installed capacity is divided among load-serving entities, in proportion to their individual expected peak loads. This produces individual requirements for installed capacity. These individual requirements must be met by either purchasing generation or contracting for its use. A contract must specify that the generator will be made available to the system if requested. Any load-serving entity that fails to own or contract for the required capacity is penalized. A second penalty applies to any generator that fails to perform when called on.

In Section 3, we propose a model of a liberalized electricity market which aims to model the long-term impacts of regulation.

3. The Model

3.1 The Wholesale Electricity Market

In this paper, we model three different technologies (baseload, shoulder and peak, respectively). Each player can own several plants of the same technology and, within each technology every plant has the same technical features (i.e., the same marginal costs).

Moreover, in this paper the clearing price, at each iteration, assumes the single-clearing mechanism, in which there is only one price at each time, and therefore all the plants (nuclear, gas or oil), selling at a given time, receive the same price for their electricity.

The computation of the clearing price is a function of the demand for that specific time (*Demand*) and of the total available capacity for baseload (K_b), shoulder (K_s) and peak (K_p) plants. The other variables defining the clearing price are the price cap ($\overline{P}$) and the marginal costs for baseload (mg_b), shoulder (mg_s) and peak (mg_p) plants The actual price $\left(P_j\right)$ is computed using equation 3.1:

$$P_j = \begin{cases} mg_b & if & Demand - K_b \leq 0 \\ mg_s & if & Demand - K_b - K_s \leq 0 \\ mg_p & if & Demand - K_b - K_s - K_p \leq 0 \\ \overline{P} & & Otherwise \end{cases} \tag{3.1}$$

Hence, equation 3.1 assumes perfect competition (which is imposed by the regulator), as the clearing price is always equal to the marginal cost of the marginal plant, except for times in which there is load shed, in which the generators receive the price cap.

3.2 Investment, Retirement and Long-Term Equilibria

A player's internal structure is a function of his initial portfolio. For any given portfolio, he computes the profit he gets from each one of his plants and how much his profit would increase if he would shut down some of his current plants or invest in new ones. Moreover, in order to choose if he is investing or divesting on a given technology, a player computes the marginal profit associated with an investment or divestment. Therefore, for any technology j and player i, the number of plants at time t ($G_{i,j}$) is computed using the following equation (3.2):

$$G_{ij} = G_{ij}(0) + \sum_t \left(I_{ij}(t) - D_{ij}(t) \right) \tag{3.2}$$

in which $G(t)$, $I(t)$ and $D(t)$ stand for the total number of plants, the number of plants in which we have invested, and the number of plants that where shut-down at time t, , respectively.

Therefore, in order to understand the dynamics of plant investment and retirement we need to look at the economics underlying these decisions. In this model, for reasons of convergence, only one company is allowed to invest or divest at a given time, in a given technology. Moreover, the players were modeled as adaptive automata, which follow the marginal profit rule when investing.

Let L represent the time since the last investment in any technology: in this simulation setting we assume that every player needs to evaluate the impact of an investment on his total yearly profit before deciding to make it. Moreover, in order to evaluate the marginal impact of an investment, avoiding "too big" jumps in the industry's structure, only one investment is allowed at a time. This means that if two different investments are profitable, at a given time, only one of them is chosen: the probability of being chosen is a function only of the number of possible investments. These are obviously simplifying assumptions of the model. In reality, during a year several investments occur (and therefore a player has no change of analyzing the current steady state of the industry), and the regulators, and governments are able to choose which types of investment will be allowed at a given time (which is not a mere function of the number of projects proposed and which may take into account the current market structure and the technology preferences of both the regulator and the government).

Investment decisions (I)

For each type of plant and for each player, when considering investing a player uses the following stochastic decision rule:

1. Each player allows for a yearly run of the market without any investment, before deciding if is worthy to invest or not: there is a need to analyze the run of the investment in the whole year, as the demand changes over time, and therefore this rule requires that during one entire yearly run of the model there is no investment. This condition ensures the correctness of the evaluation procedure, which computes the marginal value of a given investment. However, this rule implies that this model is good only in order to understand the long-term attractors of the industry's structure and the evolutionary process underlying these attractors. Additionally, it also implies that we cannot use this model to make any time forecast of how the industry is going to evolve. Even though a connection is made between an iteration and a unit of time, we do not mean the number of years simulated to have any connection with real time.

2. For each player, only investment opportunities with expected positive marginal contributions are considered.

3. At each iteration, and if more than one year has passed since the last investment, only one investment can be carried out. Therefore, only the player holding the investment opportunity having the highest positive marginal contribution is allowed to investment. This rule can be justified by the fact that this player would be the one that would be willing to pay more for a license to build a new plant. Moreover, it would be straightforward to allow several investments to take place at a given time, but this would make the calculations of the marginal

contribution of a plant more difficult to compute, as the player does not know the investment intentions of his competitors.

Retirement decisions (D)

For each type of plant and for each player, the rule followed when retiring a plant is the following:

1. Each player allows for a yearly run of the market without any divestment, before deciding if is worthy to retire a plant.

2. For each player, only retirement opportunities with expected positive marginal contributions are considered: these are retirements that increase the overall value of the portfolio of plants for a given player.

3. At each iteration, and if more than one year has gone since the last retirement, only one retirement can be carried out. Therefore, only the player holding the retirement opportunity having the highest positive marginal contribution is allowed to divest.

Long-term equilibrium

The long-term equilibrium is reached when the marginal value of an investment and divestment is negative for every player, i.e., when there is no incentive for investing or retiring a plant.

As a first intuition one would think that no such equilibrium would ever emerge, as a player who does not want to invest would most likely want to divest. However, this is most clearly not the case: from our experiments it is clear that there is an area in which no investment or divestment has a positive profit.

3.3 Energy Trading and Operational Profit

In this section, we analyze how to compute the revenue and the operational profit of each player.

Let Q_{bi}, Q_{si}, Q_{pi}, represent the quantities sold by a player i of baseload, shoulder and peak plants . For a given player i the computation of the quantities he sells from each one of his plants is a function of the demand (*Demand*) and of the total available capacity for baseload (K_b), shoulder (K_s) and peak (K_p) plants. The other variables defining the clearing price are the price cap ($\overline{P}$) and the capacity owned by player i of baseload (k_{bi}), shoulder (k_{si}) and peak (k_{pi}) plants The actual quantities are calculated using the system of equations (3.3):

$$
\begin{cases}
Q_{bi} = \max\left(\dfrac{k_{bi}}{K_b} * Demand, 0\right), Q_{si} = Q_{pi} = 0, \\
\quad \text{if } Demand - K_b \le 0 \\[2mm]
Q_{bi} = k_{bi}, Q_{si} = \max\left(\dfrac{k_{si}}{K_s} * (Demand - K_b), 0\right), Q_{pi} = 0, \\
\quad \text{if } Demand - K_b - K_s \le 0 \\[2mm]
Q_{bi} = k_{bi}, Q_{si} = k_{si}, Q_{pi} = \max\left(\dfrac{k_{si}}{K_s} * (Demand - K_b - K_s), 0\right), \\
\text{if } Demand - K_b - K_s - K_p \le 0 \\[2mm]
\quad Q_{bi} = k_{bi}, Q_{si} = k_{si}, Q_{pi} = k_{pi}, \; Otherwise
\end{cases}
\tag{3.3}
$$

Computing the operational profit for each technology and for each player:

In order to compute the operational profit of each player, we split revenue by technology. Hence, for a player i, total revenue for a given technology j (baseload, shoulder and peak) is represented as R_j and is computed by equations (3.4).

$$R_j = \left(P_t - mg_b\right) * Q_{ji} \qquad\qquad (3.4)$$

Moreover, we also need to compute fixed costs, which represent all the costs of keeping a plant running and which are not related with the generation of a given plant. The total fixed costs for a player i are the sum of the fixed costs of each technology.

Additionally, the have considered the fixed costs of each type of plant to be exogenous and therefore, for a given technology j and player i, the total fixed costs (F_i) are the sum of the fixed costs of each plant.

Furthermore, for a player i, let the available capacity of a technology j (C_{ji}) represent the remaining generation capacity after taking into account the generation sold from that technology, see equation (3.5).

$$C_{ji} = k_{ji} - Q_{ji} \qquad\qquad (3.5)$$

Hence, we are now in a condition to compute the total operational profit (OP_i) of a player i, see equation (3.6), in which U stands for the Uplift paid for declaring the capacity available if needed to maintain the system security.

$$OP_i = R_{bi} + R_{si} + R_{pi} - F_i + (C_{bi} + C_{si} + C_{pi}) * U \qquad\qquad (3.6)$$

3.4 Computing the Marginal Value

We now look at the value of a given investment and divestment opportunities and analyze how to compute them.

In order to compute the marginal value of a possible investment or retirement a player simulates the impact of that investment in the current and future prices, by looking at the value of his portfolio if this option had been executed and comparing it with the current value. This is why we need that there is no investment during an entire year before a new investment is decided.

During one year of iterations with no investment a player keeps the cumulative current profit and the profits of the other possible universes in which he invests or divests in a given technology. Therefore, in order for the valuation of the possible universes to be correct no other investment is allowed to have occurred during a year.

Consequently, if during a given year of iterations no investment has occurred a player is willing to choose a new action following the investment and divestment rule:

> *Invest (retire) a plant in a given technology if the cumulative profit of the post-investment (post-retirement) portfolio as a whole during the next year is higher than the current profit of the portfolio as a whole.*

Let us now look at the several stages of the process which enables the computation of the cumulative profit of the cumulative universes.

Stage 1: Compute the parallel price for each one of the possible investments or retirements in each technology.

The new function for computing the parallel price is given by equation (3.7), in which $I_j \in \{-1,0,1\}$ represents an investment (1), no action (0), or divestment (-1) in a plant of technology j. Moreover, the variables k_j stands for the capacity of each plant of type j. Therefore, there is a parallel price for each possible investment or retirement for each technology.

$$
P_j = \begin{cases}
mg_b & if & Demand - K_b - I_b * k_b \leq 0 \\
mg_s & if & Demand - K_b - K_s - I_b * k_b - I_s * k_s \leq 0 \\
mg_p & if & Demand - K_b - K_s - K_p - I_b * k_b - I_s * k_s - I_p * k_p \leq 0 \\
\overline{P} & & Otherwise
\end{cases} \quad (3.7)
$$

Consequently, there are two main results of the analysis of Equation 3.7:

1. The impact of a given investment on market price is independent of the player investing. This is true in this model as we have assumed that the price is always competitive, i.e., there is perfect competition in the wholesale electricity market. In general this does not need to hold, as in oligololistic industries different players have different abilities to exercise market power, and therefore to condition market prices.

2. The impact of an investment (divestment) on price is a function of the technology in which the investment (divestment) takes place and of the *cycle* to which the price refers to. As a general rule: investments on technologies with marginal costs lower or equal to (higher than) the current price tend to decrease (not to change) the clearing price. Moreover, retirements on technologies with marginal costs lower or equal to (higher than) the current price tend to increase (not to change) the clearing price.

Let us analyze a couple of examples of the second result. For example, in a cycle for which the current price is the price cap any investment may carry an impact on the price (the actual impact is only a function of the excess demand and of the dimension of the investment): in this case the bigger the investment the more likely is it to have an impact on the price; and no divestment changes the price. In the case in which the

current price is the marginal cost of the baseload plants only divestment on baseload can change the clearing price.

Stage 2: Compute the parallel quantities sold by every player and plant, for each possible investment (divestment).

Let us first analyze the case of an investment in a technology j, by a player i.

This investment affects the clearing price, for all the technologies, moreover it also affects the total installed capacity, the total capacity of technology j, and the proportion owned by player i. Therefore, in order to compute the quantities sold by a player i from each one of his plants, we need to analyze how the investment influences each one of these variables.

Consequently, for the technology j, as we are analyzing an investment, we should expect the clearing price to remain the same or decrease, and the capacity installed and the proportions owned by player i will increase.

Let P_j stand for the clearing price at a given time, after the investment in technology j is carried out, and let k_j represent the capacity of a plant of type j, and furthermore let k_{ji}^{-}, k_{ji}^{+} represent the capacity that player i owns of technology j before and after the investment, respectively. Subsequently, equation 3.8, in which RD_j is the residual demand of technology j (see equation 3.9), represents the rule use to compute the quantity sold by player i.

$$
\begin{cases}
\quad 0 & if \quad P_j < mg_j \\
\\
\quad k_{ji}^+ & if \quad P_j > mg_j \\
\\
\dfrac{k_{ji}^+}{K_j^+} * \min\left(K_j^+, RD_j\right) & if \quad P_j = mg_j
\end{cases}
\tag{3.8}
$$

Residual Demand for a technology $j \in \{b, s, p\}$:

$$
RD_j = \begin{cases}
Demand & if \quad j = b \\
Demand - K_b & if \quad j = s \\
Demand - K_b - K_s & if \quad j = p
\end{cases}
\tag{3.9}
$$

Moreover, we also need to analyze how an investment in a technology j affects the sales of any other technology $h \neq j$. In this case the equation 3.10, in which all the symbols have the meanings presented above, represents the rule used to compute the quantity sold by player i.

$$
\begin{cases}
\quad 0 & if \quad P_h < mg_h \\
\\
\quad k_{hi} & if \quad P_h > mg_h \\
\\
\dfrac{k_{hi}}{K_h} * \min\left(K_h, RD_h\right) & if \quad P_h = mg_h
\end{cases}
\tag{3.10}
$$

Let us first analyze the case of a retirement in a technology j, by a player i.

Once again, the retirement of a plant may affect the clearing price, for all the technologies, it decreases the total installed capacity and the total capacity of technology j, and it also decreases the proportion of technology j owned by player i. Subsequently, equation 3.11, in which all the symbols have the meanings presented above, represents the rule used to compute the quantity sold by player i.

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$$
\begin{cases}
\quad\quad 0 & if \quad P_j < mg_j \\[2ex]
\quad k_{ji}^- - k_j & if \quad P_j > mg_j \\[2ex]
\dfrac{k_{ji}^+}{K_j^+} * \min\left(K_j^+, RD_j\right) & if \quad P_j = mg_j
\end{cases}
\qquad (3.11)
$$

Once again, we need to analyze how a retirement in a technology j affects the generation of any other technology $h \neq j$. In this case the equation 3.9 represents the rule used to compute the quantity sold by player i.

Stage 3: Compute the total profit for each one of the parallel investment and retirement opportunities.

For each technology and player and any possible investing or divesting compute its marginal value, which is the increase in the value of the portfolio as a whole due to that specific investment or retirement. Therefore, we need to compute the additional profit of the portfolio as a whole and of each one of the technologies in the portfolio separately. Consequently, for any investment or divestment in a technology j, the new revenue for each technology as a whole is computed, for player i. Independently of the technology (*j*) in which the investment or divestment toke place, the new revenue for any technology h (which may or may not be equal to j) is described by equation (3.12),

$$
\left(P_j - mg_h\right) * Q_{hi} \qquad (3.12)
$$

Additionally, the fixed costs increase (decrease) as well for the technology in which the investment (retirement) takes place. Therefore, if F_h represents the fixed costs per unit of capacity installed of technology h, we can compute the total profit of a player i at a given time using equation (3.13):

$$OP_h = \sum_{h=b}^{p} \left(P_j - mg_h\right) * Q_{hi} - k_{hi} * F_h \qquad (3.13)$$

Finally, it is not enough to compute the additional value of an investment in a given state: we need to analyze the value of the investment (divestment) for the whole year, in a situation where no other investment (divestment) takes place. This is done for each one of the technologies by accumulating the profits for the last yearly set of iterations, since the last investment (divestment). Therefore, equation (3.14) computes the Marginal Value of an investment (or divestment) in a plant j as the sum of the operational profits for each of the stages of demand modeled (and respective durations). Moreover, in equation 3.14 D_s stands for the Duration of a given stage s of demand, $|S|$ represents the number of stages modeled, and OP_{si} represents the operational profit of player i at stage s.

$$\sum_{s=1}^{|S|} OP_{si} * D_s \qquad (3.14)$$

4. The Experiments

In this section we present the result of some of the experiments we have analyzed with our evolutionary model. The aim of these experiments is to develop new theoretical insights into the issue of fixed costs recovering in liberalized electricity markets.

4.1 Parameters

Our first task was to define meaningful parameters, which capture the behavior of players in typical liberalized electricity markets: in order to do this successfully we need to specify the parameters of generation and demand. Moreover, whenever these

parameters can be an object of policy we develop scenario analysis to test the effects of the different policy choices.

The following parameters define the demand function:

1. Price cap: price paid by generators if they fail to meet demand.

2. Lag time: the number of different stages of the demand that we are modeling. We look at the load duration curve, for a whole year, and split it into different segments (one for each level of demand).

3. Cycle index: for each iteration we compute the Lag time to which this iteration corresponds, and with this knowledge we compute the demand at that specific iteration: Cycle index: = Time-INTEGER(Time/Lag time)*Lag time+1.

4. Duration: number of hours in the year spent on cycle. In the experiments here developed we have three cycles only: baseload, shoulder and peak.

5. Average demand: expected demand for each cycle.

6. Reserve margin: represents the percentage of generation to be contracted above the expected demand, in order to ensure the security of the network. It is the extra-demand that the suppliers (retailers) need to contract in order to meet the System Operator's security standards.

7. Demand: the demand of energy at any specific iteration of the model is modeled as a Normal Distribution in which the mean is the *Demand Average* for a given cycle, and the Standard Deviation is given as a percentage of the Demand Average. Moreover, at any iteration we also define a minimum and a maximum demand level. Finally, the reserve margin is used to compute the quantity of

Demand that needs to be contracted at any specific iteration. The equation used to compute the final value of demand is:

$$\text{Demand} := \text{Normal(min , max, average, std)} * (1 + \text{safety margin})$$

The specific parameters used in these simulations were: Price cap (300); Lag time (3); Duration: baseload (5,000), shoulder (3,000) and peak (760); Average demand: baseload (15,000), shoulder (27,000) and peak (50,000); Demand min: 0; Demand max: extremely high number.

The following parameters define the generation characteristics:

1. Marginal costs: defined for each technology such as baseload (5), shoulder (15) and peak (30).

2. Fixed costs per hour: defined for each technology such as baseload (110000*1000/8760), shoulder (40000*1000/8760) and peak (3000*1000/8760). This data were collected through interviews to several companies in the British electricity market.

3. Plant capacity: defined for each technology such as baseload (1,000), shoulder (500) and peak (100).

We simulate a model with three players owning the initial installed capacities described in Table 4.1 (values in MW). Therefore, we look at an oligopoly in which the initial technological structure of the different players is different.

In this case we simulate an industry in which the players have different technologic structures: the total installed capacity is 35,000 MW.

TABLE 4.1: CAPACITIES

|	Player 1	Player 2	Player 3
Baseload	10,000	5,000	0
Shoulder	5,000	5,000	5,000
Peak	0	0	5,000

4.2 The Impact of the Demand Cycles

As a first introduction to the issue of investment in electricity markets let us analyze the results of a simulation in which demand always presents the same expected value (having no cycles, and therefore in which the load duration curve is flat), and compare it with the results of the simulation in the baseload scenario. In the experiments with Cycles the parameters used were average demand for baseload (15,000), shoulder (27,000) and peak (50,000), with durations of baseload (5,000), shoulder (3,000) and peak (760). In the experiments with No_cycles the average demand was defined as 22,000 (the average of the cyclic demand).

The results depictured in Figure 4.1 are very interesting indeed as they clearly illustrate the importance of demand cycles in the shaping of the industries' structure. Even though the average demand is the same in the two cases, the behavior of the market structure was somewhat different: In both cases the generation firms are reducing the quantity of installed capacity, increasing prices. However, when there are no cycles this reduction is more noticeable.
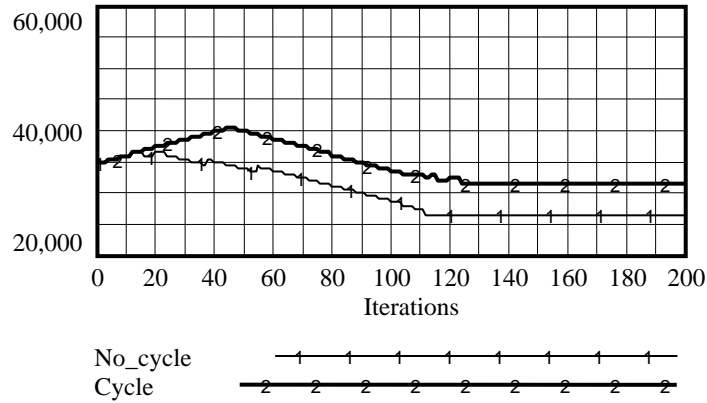
FIGURE 4.1: TOTAL INSTALLED CAPACITY

Moreover, looking at the behavior of the Excess Capacity in the industry, see Figure 4.2, we can understand better what is happening in both cases. Whilst in the case of No_cycles the Excess Capacity converged to zero (as the generators minimize the investment and increase prices to the minimum security level), in the case of Cycles (which better describes how real electricity markets work) we see the excess capacity is very cyclical, being around zero only in the case of the shoulder market.
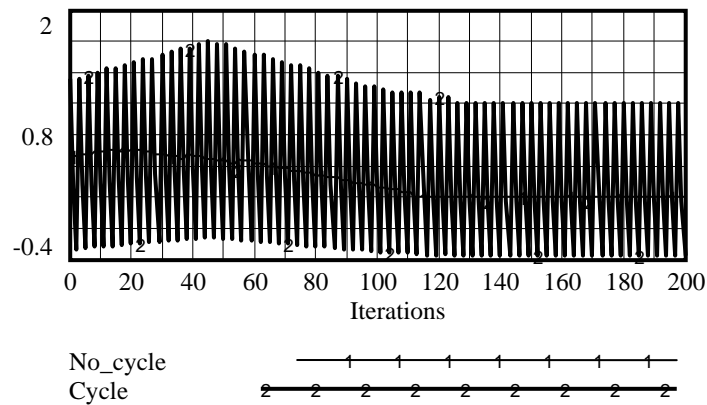
FIGURE 4.2: EXCESS CAPACITY

Having established this basic result we now concentrate on the case of the cyclical load duration curve.

4.3 Price Caps and the Duration of Peak Demand

We now examine the impact of price Caps and Duration of Peak Demand on the behavior of investment and market structure.
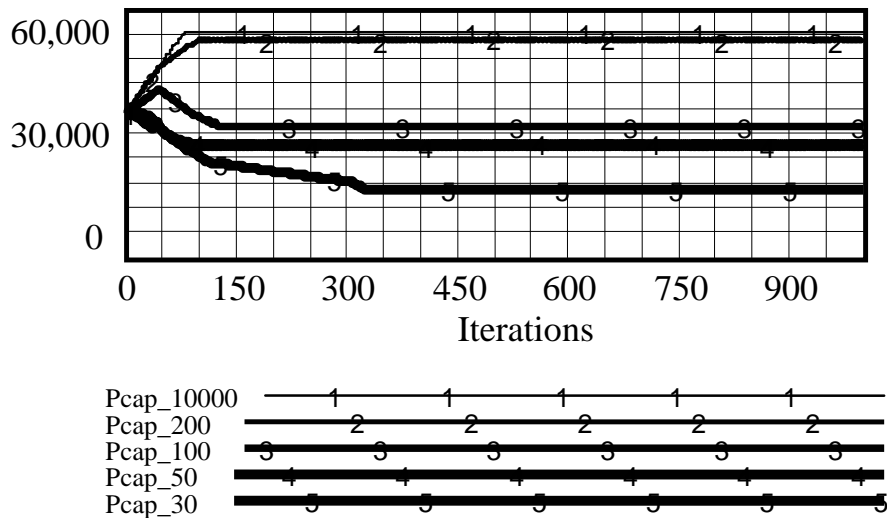

FIGURE 4.3: TOTAL CAPACITY AND PRICE CAP

In Figure 4.3 we represent the results of the simulations for several different price Caps, respectively, 30, 50, 100, 200 and 1000 £/MWh. The initial results by simulating a price cap of 30 £/MWh, 50 £/MWh, 100 £/MWh and 200 £/MWh, show that, as expected, by reducing the price cap the investment decreases, increasing the total demand shed in equilibrium. Hence, the avoidance of price spikes conduces to low long-term investment and, as a policy recommendation, it seems that the price cap needs to be high enough to ensure the necessary investment.

However, the surprise results from the experiment with a price cap of 1000 £/MWh are striking: when the price cap is too high no investment takes place: this is the worst case scenario as we have very high prices and very high load shed at the same time.

In summary, these experiments with several different price caps reveal the complexity of price-cap policy: the impact of this parameter on the evolution of the market structure is non-linear, it cannot be too low or too high. Therefore, the regulation task is to find a value for this parameter that creates the right quantity of investment. Moreover, these results are also quite revealing of the capability of a liberalized market to increase the generation capacity: it will fail to deliver the needed investment unless the regulators intervene. Furthermore, strictly interconnected with the price cap is the duration of each one of the markets. This duration is exogenous and is not completely controlled by the regulatory authorities.

We now look at several different scenarios for these durations, attempting to shed light on this issue: is it better if all the energy is traded in the futures market or just in the spot market. How does the different duration loads affect the market investment?
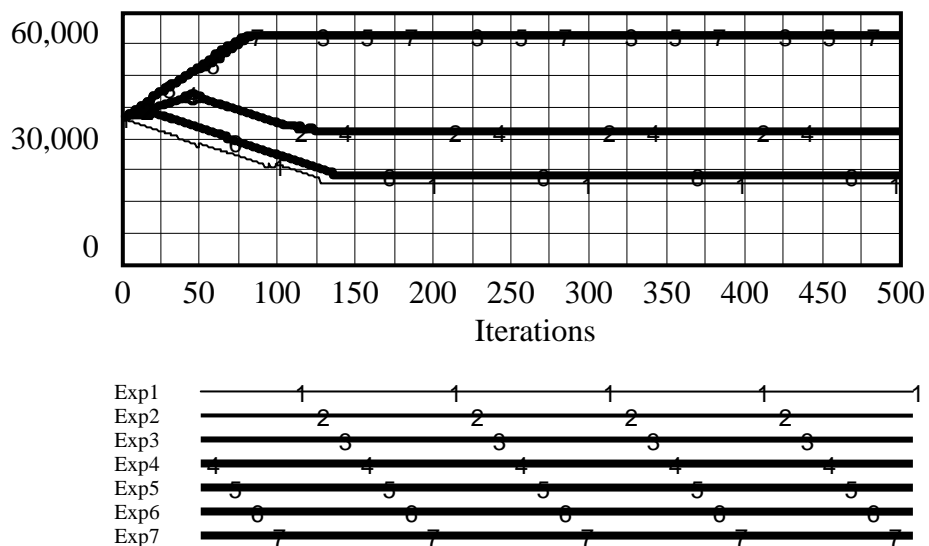
FIGURE 4.4: TOTAL CAPACITY AND DURATIONS

Therefore, these experiments can be grouped in three different sets. The first group includes Exp1 (baseload 8760, shoulder 0, peak 0) and Exp6 (baseload 8000, shoulder 0, peak 760). The second group includes Exp2 (baseload 0, shoulder 8760, peak 0) and

Exp4 (baseload 5000, shoulder 3000, peak 760). Finally, the third group includes Exp3 (baseload 0, shoulder 0, peak 8760), Exp5 (baseload 3000, shoulder 3000, peak 2760) and Exp7 (baseload 5000, shoulder 0, peak 3760).

Subsequently, in order to explain these results, we need to identify their main driver, which we would think to be the average demand in each one of these experiments. The experiments in Group 1 have average demands of 15000 and 18000, respectively. The experiments in Group 2 have average demands of 27000 and 22100, respectively. Finally, the experiments in Group 3 have average demands of 50000, 30100 and 30000. Consequently, average demand partially explains the total investment in the industry, as the groups with higher demand show more investment. However, the wide difference between the average demands within the same group indicates that this is not the only variable at work.

**4.4 Reserve Margin in the Long-Run and the Uplift**

We start by looking at the Reserve Margin: this is defined as the quantity of generation that electricity retailers are asked to purchase above the expected demand, in order to ensure the security of the system.

In these experiments, we assumed that the demand of electricity is increased by a given percentage (0%, 10%, 20% and 30%) above the expected demand, and then we analyze the results of these policies. Figure 4.5 shows that the higher the reserve-margin the higher the total investment: this is a logical outcome of the increased demand. However, this instrument by itself was not able to provide the incentive needed to ensure the long-term security of the system, as in any of the experiments analyzed the peak demand is not completely satisfied.
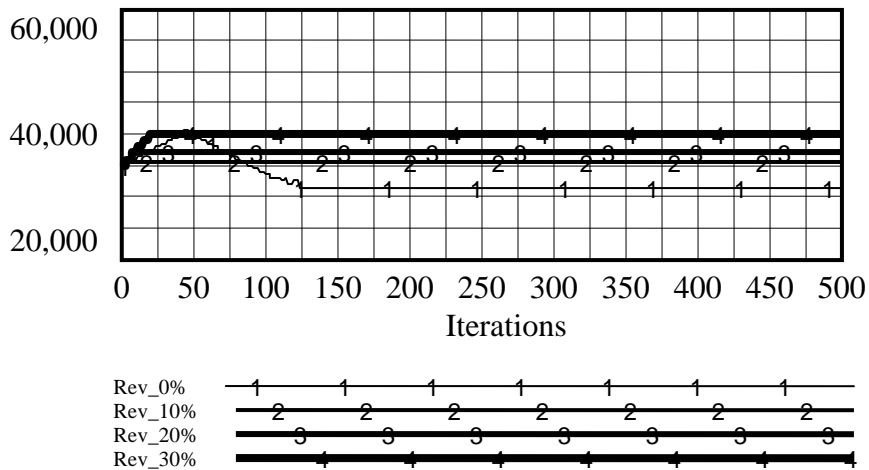
**FIGURE 4.5**: TOTAL CAPACITY AND RESERVE MARGIN

Moreover, by analyzing the composition of the generation structure, see Figure 4.6, we can conclude that even a slight increase in demand, due to the reserve margin, leads to important changes in the relative value of the different technologies. In this case, the presence of a reserve margin increases the value of all the technologies, allowing for the maintenance of the shoulder technologies and increasing the investment in baseload.
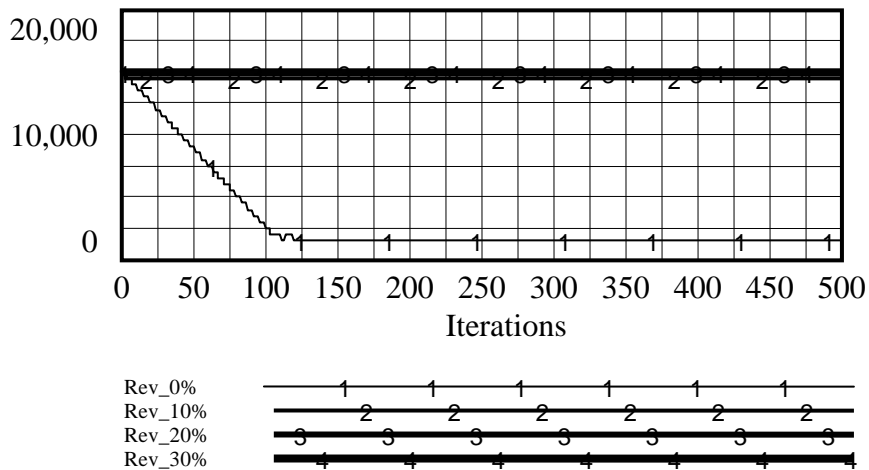
FIGURE 4.6: SHOUDER TOTAL CAPACITY AND RESERVE MARGIN

Therefore, in order to provide an additional incentive for investment in generation capacity, a second very important instrument of Regulation policy influencing the

electricity prices are the Capacity Payments, which are used to remunerate the presence of unused capacity.
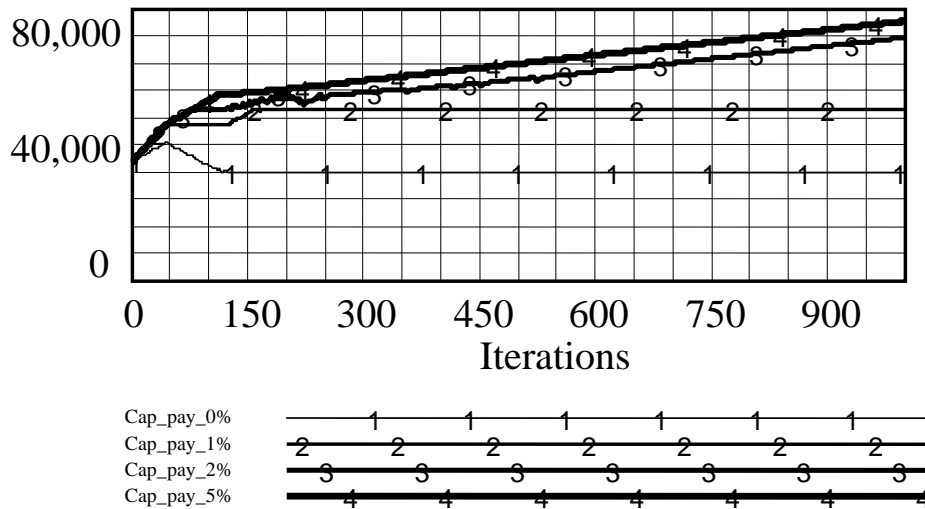
FIGURE 4.7: TOTAL CAPACITY AND CAP. PAYMENTS

The set of experiments represented in Figure 4.7 show that a small capacity payment of 1% of the current price, for all capacity available and not used, is enough to ensure the right incentives for investment in new capacity. Moreover, it also shows that this instrument is very sensitive to small increments. By duplicating the incentive to 2% of the current price the Regulatory authority is able to increase the investment to levels well above the required by the system. Furthermore, this result also shows that an increase of the capacity payments from 2% to 5% does not increase substantially the amount invested. Hence, these experiments show that the main task of the regulatory authorities is to define a level of capacity payments that give the necessary incentive to investment, at the minimum cost.

In addition, by analyzing the proportion if the different technologies, Figure 4.8, we conclude the Capacity Payments are very important in shaping the generation structure. In this case whilst the 1% payment is mainly directed towards the investment in

shoulder technologies, for payments of 2% and 5% are mainly the peak plants who benefit from the investment subsidy.
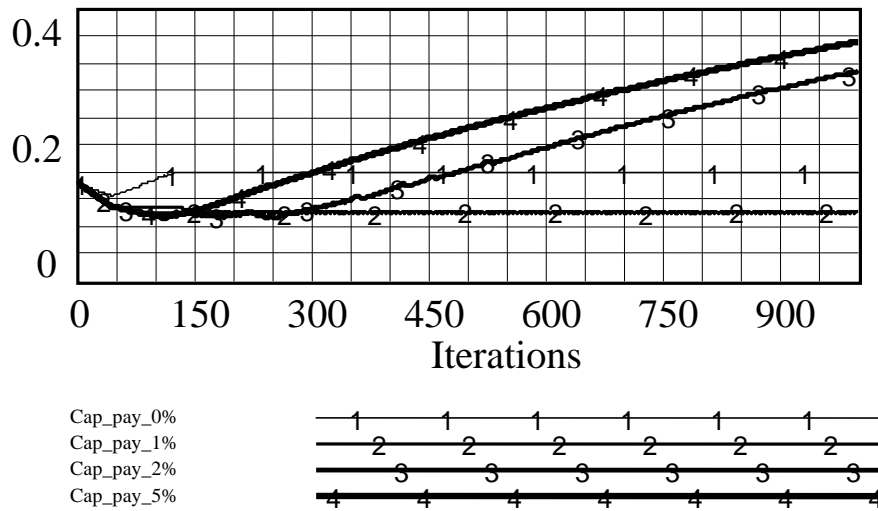

FIGURE 4.8: PEAK PROPORTIONAL CAPACITY

4.5 Energy Price Uncertainty and Investment

We now look at the relationship between energy price uncertainty and the quantity invested. It is a common belief that uncertainty increases the value of a right to invest (look at the theory of real options in which the price volatility increases the value of an option to invest). Moreover, in the electricity markets setting it has been argued that the generation companies used price uncertainty as a way to increase "security premiums", and therefore charging higher average prices, increasing the value of their portfolio. In this section we analyze this claim. The first set of experiments assumes a price cap of 100 £/MWh, and the results are represented in Figures 4.9 and 4.10.
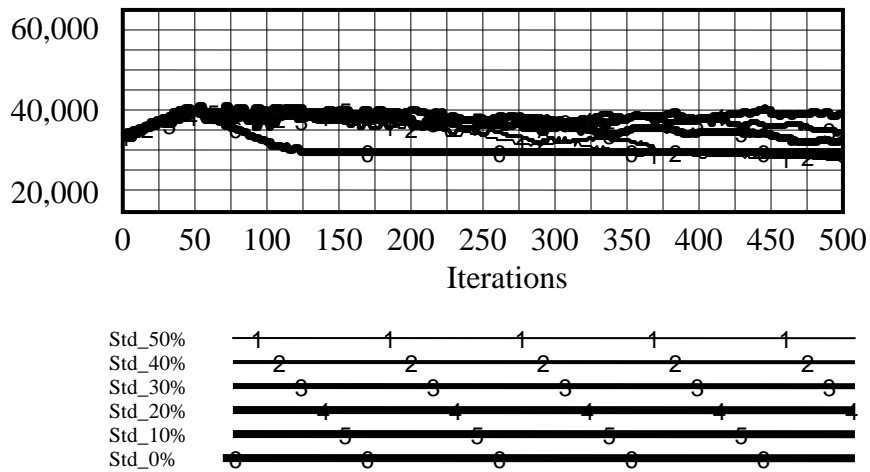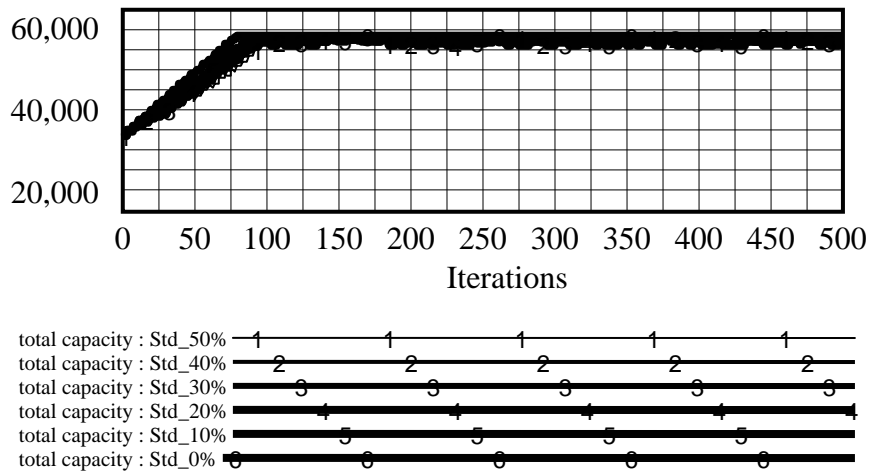
FIGURE 4.9: TOTAL CAPACITY AND PRICE UNCERTAINTY

It seems that increased uncertainty leads indeed to more investment, when the standard deviation of the price is below 30% (and presenting its highest level with 20% of standard deviation). However, as uncertainty increases towards 40% and 50% the amount of investment is bellow the one attained with zero standard deviation. Moreover, we also wanted to know if there is an implication of price uncertainty on the value of the different technologies. We have analyzed the investment in the different technologies and the result on the Peak plants is presented in Figure 4.10.
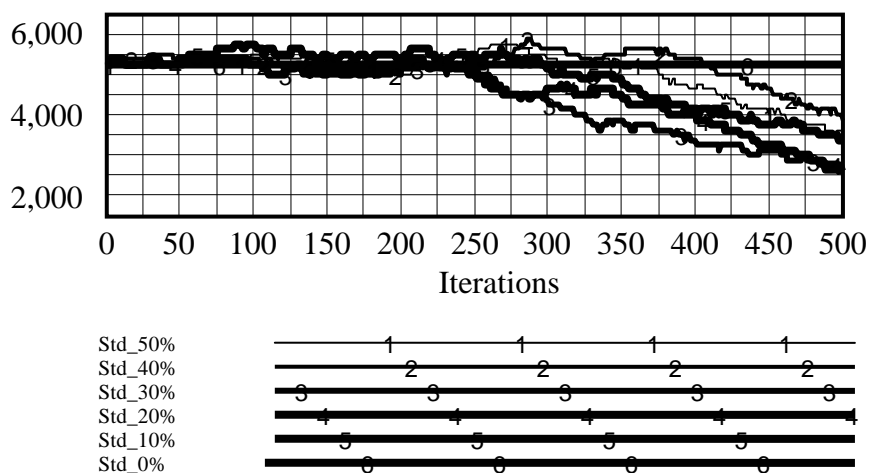
**FIGURE 4.10**: PEAK CAPACITY AND PRICE UNCERTAINTY

Figure 4.10 most clearly shows that uncertainty reduces the value of Peak plants: this result clearly contradicts any common sense in these matters, as one would expect the presence of price uncertainty to be beneficial to Peak plants. Therefore, in order to probe further into this issue, we have conducted a second set of experiments on price uncertainty, in which the price cap is set at 1000 £/MWh: the results are presented in Figures 4.11 and 4.12.

FIGURE 4.11: TOTAL CAPACITY AND PRICE UNCERTAINTY: 1000 £/MWh CAP

Figure 4.11 shows that in this case the zero uncertainty case represents an upper-bound on the volume of investment, and therefore is the case in which capacity is more valuable.

Moreover, Figure 4.12 shows that the proportion invested in baseload increases with uncertainty of the energy price, decreasing the investment in shoulder plant: this strange behavior is explained by the number of hours that plants run. The increased price uncertainty means that the likelihood of a plant running is reduced, and therefore its value is decreased.
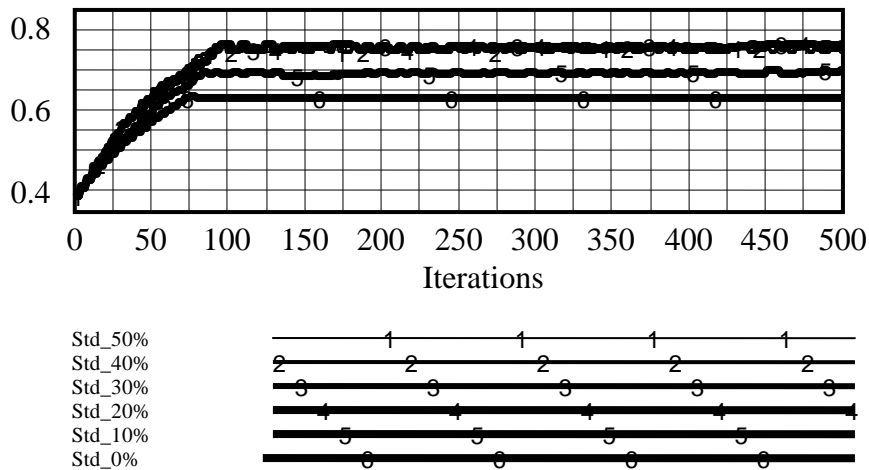
FIGURE 4.12: PROPORTION OF BASELOAD AND PRICE UNCERTAINTY

Therefore, as a defensive strategy, the players prefer to invest in baseload: at this stage it is important to realize that all this analysis assumes a single-clearing market, in which all the players receive the same price, independently of the technologies used.

5. Conclusion

In this paper we have looked at the issue of investment in liberalized electricity markets in which players hold a portfolio of several technologies. Moreover, this analysis is centered on the single-clearing market, in which there is only one price for the electricity generated at a given time of the day. Further, the market is regulated and the prices are equal to marginal costs, as it would happen under perfect competition.

We show that the market in the long-run tends to converge towards an equilibrium in which the marginal value of any possible investment (or divestment) is negative for every player. Moreover, it is also shown that in this regulated liberalized electricity market:

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- The impact of a given investment on market price is independent of the investing player; that is, of the particular portfolio of technologies owned by the investor.

- The impact of investment (or divestment) on price depends on the type of investment and on the quantity demanded at any given price.

An evolutionary model of investment (divestment) on portfolios of plants is developed. Players compute the marginal contribution of each possible investment (or divestment) for the value of the portfolio, before deciding which action to take.

Through the different simulations and experiments, several conclusions are possible:

1. Cyclical behavior of demand implies excess supply at baseload times and load shed at peaks.

2. Price caps and investment do not have a linear relationship. Even though increases of the price cap tend to lead to more investment, however if the price caps are too high no more investment will take place (but the consumers pay higher prices).

3. Liberalized electricity markets tend to be short of capacity, as players minimize investment in order to increase prices (due to low elasticities). Therefore, there is a need for regulation.

4. Market durations are crucial for investment as, when a certain level of demand does not last long enough, it will not be profitable to serve it and demand will be shed.

5. The higher the reserve margin the higher the total investment. However, and most importantly, this instrument by itself failed to deliver reliability, and therefore demand was shed.

6. The evolution of the technological structure is influenced by the presence of reserve margins and capacity payments, even though it is a side effect of these policies.

7. Capacity payments lead to more investment. However, the regulator needs to define the exact quantity paid (and this is a very difficult decision as the system is very sensitive to this payment).

8. Most surprisingly, our results suggest that increased price uncertainty has a non-linear relationship with investment. Low uncertainty increases investment whereas high uncertainty decreases investment. This is the product of the interaction of two opposite forces. Price uncertainty provides price spikes that increase the value of the running plant, creating incentives for investment; however, too much uncertainty decreases the value of marginal plants, leading to lower investment.

9. The impact of uncertainty on the value of plants and on the evolution of the market structure depends of the price caps. When the price cap is very high then the higher the price uncertainty the higher the investment (as the price spikes are so high that they can accommodate for excessive capacity), otherwise the lower the uncertainty the higher the investment (as price uncertainty decreases the value of marginal plants).

In conclusion, the use of an evolutionary model of the electricity industry proved valuable towards the analysis of the long-term impact of short-term policies, such as price caps, reserve margins or capacity requirements.

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