Investments in generation capacities in an oligopolistic electricity market *

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This article focuses on oligopolisitic strategies of investment in a context of uncertain growth of future demand. Investment in an electricity market is modelled with a long-term (30 years) stochastic Cournot game in production and investment. This numerical modelling differs from game theory models that study strategic behaviours in investment with theoretical two-stage oligopoly modelling and offer a description of the electricity market where demand and production capacities do not evolve over time.
The growth of demand is random. Players choose their levels of investment in generation capacities for each future date and the capacities made available on the market. The decision process is one-stage but investment and production decisions applying in say year 2010, are in feedback over the random annual growths until 2010. Results suggest that restriction in production and capacity development by large players opens some space for small players to invest first and increase their market shares. They also suggest that commitment to a larger production by large players can delay the growth of the small players and yield greater expected profits to large players in the long-run.

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1 INTRODUCTION

Modelling investment in production capacities in liberalised electricity industries remain a relatively unexplored subject. Investment decisions in a deregulated environment are indeed complex and risky for the generators given the volatility of market prices, the uncertainty regarding competitors' investment and generation decisions as well as the high regulatory risks in electricity markets.The published literature to date has focused primarily on the weakness of the incentives to invest in generation capacities in a market environment, as well as on corrective instruments such as capacity obligations and capacity payments. This is especially relevant for peak capacities that enable supply and demand equilibrium of a non storable good in real time. Several contributions including von der Fehr and Harbord (1997); Murphy and Smeers (2002); Boom (2002, 2003) study investments in new generation capacities with theoretical two-stage oligopoly models: after investment has been decided, all future decisions and information are subsumed into one future period. In spite of their dynamic structure (two-stage decision making), these models offer a description of a non-evolving electricity market: investment takes place in only one date,and for one demand. Progressive and stochastic evolution of demand, and scheduling of investments in an oligopoly remain open issues.

In contrast, we use a numerical stochastic oligopoly model, with one-stage decision but multi-period actions: the model aims at describing the sequencing of investments in new capacities on a long-term horizon (2030) with an uncertain demand trend. There are a few examples of numerical models focused on expansion planning with imperfect competition. Ventosa et al. (2002) developed a Cournot model and a Stackelberg model of expansion planning; only one of the competitors is investing in one technology (combined cycle); and the characteristics of future demand are certain. Botterud and Korpas (2005) use real option theory to investigate optimal timing and amount of investment under uncertain future demand evolution in an imperfect market; only one producer is optimising his investment decision whilst the others are represented by behaviour rules relating their investment to price. Pineau and Murto (2003) developed a model of a Cournot game of investment and production with uncertain demand evolution in the Finnish market over the next 10 years. Players decide on production and investment in generation capacities for each of the five future periods, contingent upon the state of the world (s.o.w). Such one-stage but s.o.w.-contingent strategies have been studied and termed as 'sample adapted open-loop' strategies by Haurie et al. (1990). The model presented here was originally derived from the one in Pineau and Murto (2003). In particular, it has the same game structure: a Cournot game in investment and production with uncertain demand evolution over several time-steps. Our model however differs from theirs in several directions. In particular, it spans over a much longer-term horizon (30 years) and offers a wider set of production technologies and more detailed description of the load duration curve.

We choose to use a model based on Cournot games, despite their well-known limitations for representing electricity markets (Ventosa et al. (2005)). Admittedly they tend to overestimate oligopoly market power, and result in too high prices and probably, in too low investments because new entrants and regulatory threats are not taken into account. Theoretical results by Murphy and Smeers (2002) also suggest that this may be more pronounced in open-loop than in closed-loop equilibrium. However Cournot models are more flexible, tractable and, according to Ventosa et al. (2005), are the more suited approach to long-term planning since they can consider a large set of participants.

Section II deals with the mathematical structure of theoretical models of competition and investment in capacity in the electricity markets; it specifically considers the limitations and advantages of the sample adapted open-loop equilibrium for discussing long-term planning in imperfect markets. Section III reports the modelling hypotheses and data. Section IV presents and analyses simulations carried out for a German-like electricity industry. In Section V, some conclusions are outlined and possible extensions discussed.

2 GAMES OF INVESTMENT IN ELECTRICITY MARKET COMPETITION

This section summarises the general structure of game-theoretical models of imperfect competition and investment in electricity markets that can be found in the literature (section 2.1). It identifies the differences with the structure used in our numerical model (section 2.2).

2.1 Theoretical two-stage models

Several theoretical models of capacity investment in electricity markets, in particular von der Fehr and Harbord (1997); Murphy and Smeers (2002); Boom (2002, 2003), can be seen as typical of the following, more general and theoretical model.

There are two dates of actions: a first when investment is made, and a second one when electricity is produced[1]. There are N players (producers), indexed by $i = 1, \dots, N$. Demand for generation is both time varying and random. It is characterised by a state of the world, $s \in S$, which indicates either the load period served or the demand uncertainty realised (Pignon et al. (2004)) or both in the case

[1] All productions and consumptions take place at a single node.

ofMurphy and Smeers (2002). It is distributed with the probability distribution $\mu(ds)$. Players take two successive actions:

1. In period one, they invest in generation capacities, $I_i \in \mathbb{R}^L$, where L is the number of generation technologies considered. Boom (2003) describe players that also commit to a retail price. These investments (and eventually retail price) will be identical for all possible realisations of the random variable.

2. In period two, players make offers $a_i(s)$ for each state s of the demand. Depending on the model, offers (one for each player and capacity type $\ell \in L$) are supplies of power, as in Murphy and Smeers (2002), or price bids on reverse auction (von der Fehr and Harbord (1997); Boom (2002, 2003)). In the former case where the players compete on quantities, pure strategies are considered; in the latter case, mixed strategies are also considered.

Demand and players' offers in state s determine the spot price $p(s)$. Finally, profit is determined by the capacities called or offered, the spot price and when relevant, the retail price. The expected profit Π_i of the player i can be seen as a function of the couple of the N actions in the first and second periods, $\Pi_i(I, a)$.

2.1.1 Solution

Two solution concepts for defining the optimal strategies are found in the literature.When solving for a *closed-loop equilibrium*, second-period actions $a_i(s)$ are defined by strategies (or decision rules) that fix what will be produced by a player i depending on the first-period actions I of *all* the players, $a_i(\cdot, s) : I \mapsto a_i(I, s)$. Such equilibrium corresponds to a two-stage decision making process: second-period actions are chosen on the basis of the observed first-period actions. First-period actions are chosen with consideration of how they will influence the choices made in second-period.

The *open-loop equilibrium* (or more precisely the sample-adapted open-loop equilibrium, see Haurie et al. (1990) approach) considers a smaller set of second-period decision-rules, constant decision rules: $a_i(\cdot, s) : I \mapsto a_i(s)$. The underlying decision-making process is one-stage since each player commits simultaneously to his first and second period actions simultaneously.

First period actions $I^\star$ in the open-loop equilibrium may differ to those in the closed-loop equilibrium, $I^\#$. Note, however,that in an open-loop equilibrium, second-period actions are dynamically coherent with first period actions, in the sense that $a_i^\star = a_i^\#(I^\star)$.

Murphy and Smeers (2002) proposes an interpretation of the open-loop and closed-loop solutions in electricity markets.

- Closed-loop: the second-stage of the game represents a spot market. The price is interpreted as the spot price.

- Open-loop: decisions on investment generation capacity and production are made simultaneously: . Hence there is no spot market. The emerging price is the equilibrium price of energy sold through long-term bilateral contracts or financial forward contracts.

We come back to the interpretation of the open-loop equilibrium within the context of our model in section 2.2

2.1.2 Interpretation and limitations

Results concerning investment obtained in the above framework rely on a certain number of assumptions that are seldom recalled. Murphy and Smeers (2002), however, comment them in detail. In particular two such assumptions are worth noting as caveats:

- The description of load is typically for one year. Since the lifetime of a plant is much longer, this implies that investment costs are annualized costs and more importantly that the pattern of demand is assumed to remain constant over the lifetime of a power plant. In particular, this implies no growth and no further changes to offers once made.

- Existing capacities are not taken into account although these capacities, their mix of technologies and their size are expected to affect their competitiveness.

In contrast, the approach developed in this paper takes into account the interdependence between the profitability of investments made at different dates and by different players. We represent existing capacities and their progressive phasing out, load growth at each time-step and the uncertainty of this growth. Thje major drawback of this approach is the reliance on an equilibrium concept that remains computationally accessible with a intermediate level of details on technologies. However it does not violate the Nash-Cournot sample-adapted open-loop equilibrium in pure strategies (Haurie et al. (1990)).

2.2 A one-stage Cournot game of long-term investments planning

In this section, we present the mathematical structure of the model used for our numerical exercise.

this formulates the investment-planning problem in the power sector as an oligopoly game. The mathematical structure is essentially the S-adapted open-loop model presented above in section 2.1 but here, decisions comprise of the different investments and operating levels undertaken at *several* time-steps $t = 1, \dots, T$. These time-steps divide a long-term period during which load demand growth occurs at random rates while retirement of initial generation capacities occurs exogenously.

2.2.1 The uncertain evolution of demand

- The uncertain *evolution* of load demands[2] from $t-1$ to t is characterized by a state in $S = \{s_1, \dots, s_p\}$. A scenario of demand evolution is $\omega \in \Omega = S^T$. Within a scenario ω, the evolution of demand in step t is therefore given by the coordinate mapping $s^t(\omega) = \omega_t \in S$.
- The uncertain *level* of load demands in time-step t is given by the successive random evolutions from time-step 1 to t, the t-uplet $\gamma_t = (s^1, \dots, s^t) : \Omega \to S^t$.

Demand scenarios, are described as a time-homogeneous Markov chain. The probabilities $\mathbb{P}(s^{t+1} = s' | s^t = s)$, for each $s, s' \in S$, are independent of t.

Each player defines his actions in time-step t as relative to the random trajectory γ_t that will determine demands[3] in t. Decisions will therefore be defined as functions of the random variable γ_t.

2.2.2 Investments, generation capacities and production levels

- q is the vector of the operating levels $q_{i\ell jt}$ of each player i with capacities of technology ℓ during load period j of time step t. The corresponding production levels are $h_j q_{i\ell jt}$.
- I is the vector of the investments $I_{i\ell t}$ of each player i in generation capacity of technology ℓ in time-step t.

Investments in technology ℓ in time-step t enter in operation d_ℓ time steps after, in $t+d_\ell$. In each scenario ω, operating levels $q_{i\ell t+d_\ell}$ are constrained by the capacities[4] in $t + d_\ell$:

$$q_{i\ell\, jt+d_\ell}(\gamma_{t+d_\ell}) \leq K0_{i\ell\, t+d_\ell} + K_{i\ell\, t+d_\ell}(\gamma_{t+d_\ell}) \quad \text{for all } j \tag{1}$$

[2] There is one demand for each load period.

[3] Demand is also determined by the price.

[4] The actual constraint we use in the model includes an exogenous level of availability for each technology and load period.

where $K0_t$ is the amount of remaining initial capacities at time-step $t + d_\ell$ and where $K_{t+d_\ell}(\gamma_{t+d(l)}(\omega))$ is the sum of past operational investments at time-step $t + d_\ell$ of scenario ω: it is given by the following equation, with $K_\tau = 0, \tau \leq d(l)$

$$K_{i\ell\, t+d_\ell}(\gamma_{t+d_\ell}) = K_{i\ell\, t}(\gamma_t) + I_{i\ell\, t}(\gamma_t) \tag{2}$$

which is equivalent to, for all $t > d_\ell$,

$$K_{i\ell\, t}(\gamma_t) = \sum_{\tau=1}^{t-d_\ell} I_{i\ell\, \tau}(\gamma_\tau) \tag{3}$$

2.2.3 Objectives and competition game

The objective of each player i is to maximise his expected present-value profit Π_i under the production constraints. The equilibrium of this competition game is as defined as in section 2.1,

$$\begin{aligned}
\Pi_1(I^\star, q^\star) &\geq \Pi_1(I_1, I_2^\star, \ldots, I_N^\star, q_1, q_2^\star, \ldots, q_N^\star) \\
\Pi_2(I^\star, q^\star) &\geq \Pi_2(I_1^\star, I_2, \ldots, I_N^\star, q_1^\star, q_2, \ldots, q_N^\star) \\
&\ldots \\
\Pi_N(I^\star, q^\star) &\geq \Pi_2(I_1^\star, I_2^\star, \ldots, I_N, q_1^\star, q_2^\star, \ldots, q_N)
\end{aligned}$$

where for each i,

$$\begin{aligned}
I_i &\equiv (I_{i1}(\gamma_1), \ldots, I_{it}(\gamma_t), \ldots, I_T(\gamma_T)) : \Omega \to \mathbb{R}^{L\times T} \\
q_i &\equiv (q_{i1}(\gamma_1), \ldots, q_{it}(\gamma_t), \ldots, q_T(\gamma_T)) : \Omega \to \mathbb{R}^{L\times J\times T}
\end{aligned}$$

2.2.4 Interpretations of the open-loop equilibrium and modelling consequences

A forward interpretation. As mentioned above, Murphy and Smeers (2002) proposed to interpret the open-loop equilibrium as a market where there is no spot but rather where investment and long-term contracting are simultaneous. The price obtained is the equilibrium price for energy sold through long-term bilateral contracts or financial forward contracts. It is then logical to rely on long-term elasticities for models using this type of equilibrium. Cournot models with long-term elasticities tend to obtain prices that remain into a reasonable range but quantities appear to understate those of a competitive market. This could be acceptable considering that adaptation potential enters the picture in the long-term. Several other difficulties arise, however. In the case of a sample-adapted equilibrium, long-term contracts and contractual prices must be contingent not only on the load period but also on the realisation of a random variable for demand uncertainty. In addition contracts implicit in long-term models can have a maturity up to the horizon of the model: thirty years in the case of our model. Actual electricity contracts have shorter time horizon (Smeers (2004)).

A spot interpretation. Should one therefore turn to interpret the prices obtained at the open-loop equilibrium as a rough representation of a spot market? This appears an acceptable compromise since quantities and therefore prices are dynamically consistent with previous investments (in the sense defined in section 2.1). However, a representation of the spot market would call for short-term elasticities. In a Cournot game, this tends to yield very high prices. Consumers confronted to such prices over a long period would adapt their equipements and reduce their consumptions.Moreover, given that wholesale buyers on the spot market (i.e. the retail suppliers) in fact anticipate prices and quantities rather than final consumers, there is also a possiblity of market adaptation.Indeed retail suppliers can choose to promote and subsidise investment in energy efficiency for consumers in anticipation of high prices.

Another possibility is that suppliers may offer contracts with higher retail prices and lower supply reliability (see Joskow and Tirole (2004)) if a sharp rise in spot prices is anticipated. The demand function is therefore more price elastic in the long run. The anticipated prices and consumptions could be seen as the equilibrium of a one-stage game where producers take the retailers' demand-side management actions as given, while retailers take the producers' quantities as given[5]

3 A MODEL OF LONG-TERM INVESTMENT AND OPERATIONS

In this section we describe the implementation for our numerical exercise[6] of the game presented in section 2.2

We extend Pineau and Murto's model in several directions. The representation of uncertainty as an event tree is kept. However not only binomial but also p-nomial trees can be modelled. This allows us to investigate the sensitivity of the initial investment to the discretization of uncertainty [7]. A longer-term horizon of30 years rather than 10 year is considered[8]. This is important when examining

[5]This would of course require a more formal description.

[6]The model is written in GAMS as an optimisation problem for each player and for the fringe. The game equilibrium is obtained by solving iteratively the optimisation problem of each player and of the fringe, taking the decisions of the other (investment and productions) as given and fi xed at the level of the solution obtained previously. Convergence is usually obtained after 11–13 iterations.

[7]There is of course a trade-off between the order p of the tree and the number of periods of its unfolding (curse of dimensionality).

[8]So that the number of time steps had to be increased up to $T = 15$. As a consequence, the tree

investments triggered by the phasing out of existing capacities. Large baseload capacities are expected to be phased out at the start of the next decade. Finally, several distinct technologies options are described and are available to the players for both investment and production. Technologies differ by their investment costs, annual fixed costs, operation costs, and the lag between investment and operations commencing. We use actual data from the German electricity industry: initial capacities, forecasted dates of phasing out and costs of investment and variable costs. Year 2005-2006 prices (from the German power exchange EEX) and consumptions are used for calibration of the initial time step. The first time step, $t = 1$, stands for the years 2006–2007.

- Five load periods, $J = 5$, are described for representing the hourly demand of power during a year of each time step.
- Five players will be considered, $N = 5$, four of them exert market power, the fifth one is a competitive fringe.
- There are five production technologies, $L = 5$: nuclear, brown coal, hard coal, combined cycle gas turbines (CCGT) and peakers. In the model, coal powerplants and CCGT require two time steps, i.e. four years to be installed, $D(\ell = 2, 3, 4) = 1$. Nuclear requires three time steps and peakers, one time step.
- There is no uncertainty on the level of demand in $t = 1$. Demand growth is uncertain from $t = 2$ to $t = 5$. After time step $t = 5$, the evolution of the demand parameter is totally determined by the scenario which has unfolded. Therefore, $\Omega = S^4$ (see section 2.2). ¿From $t = 2$ up to $t = 5$, the load evolution $s^t(\omega)$ is in $S = \{\underline{s}, \overline{s}\}$. Transition probabilites are defined by $p(s'|s) = 1/card(S)$ for all $s, s' \in S$.

3.1 Inverse demand and random evolution

Demand is represented through a linear inverse demand function that relates the price p_{jt} to the total power $Q_{jt} \equiv \sum_{i\ell} q_{ij\ell t}$.

$$p_{jt} = a_j - \beta_t \, b_j \, Q_{jt} \tag{4}$$

does not unfold until the end of horizon, still for dimensionality reason.

where the random variable β_t over Ω is defined by

$$\beta_1(\omega) = 1 \tag{5}$$

$$\beta_t(\omega) = \frac{\beta_{t-1}}{(\omega)(1 + s^t(\omega))}, \quad \text{for } 2 \leq t \leq 5 \tag{6}$$

$$\beta_t(\omega) = \beta_5(\omega) \left(\frac{\beta_5(\omega)}{\beta_1} \right)^{\frac{t-5}{4}}, \quad \text{for } t > 5 \quad . \tag{7}$$

In our interpretation of the open-loop equilibrium (see section 2.1), the prices obtained in *future* time steps are the one that players anticipate for the future years. Long-term demand is more price responsive and we therefore use long-term elasticity with value $\eta = -0.9$ as in Pineau and Murto (2003).

After $t = 1$, the random evolution of the demand parameter g is assumed to be either stability ($\underline{s} = 0$) or growth ($\overline{s} = 0.01$). In the sustained growth scenario $\omega = (\overline{s}, \overline{s}, \overline{s}, \overline{s})$, the slope of demand curves increases so that electricity consumption would need to increase by 1%/yr in order to keep prices constant at their reference value. Figure 1 displays the total demand for each of the 16 scenarios, assuming that prices are kept constant to their reference values.

Figure 1: Demand growth scenarios (with prices kept constant). MWh.
All scenarios start from a unique point at 431 MWh. They have been shifted verticaly for clarity.

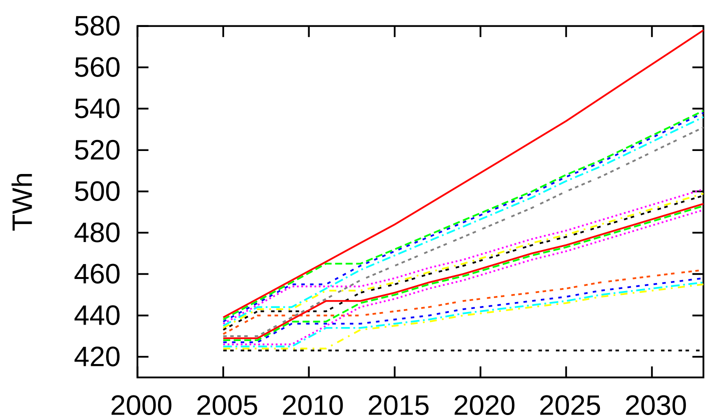


Table 1 displays for each load period, $j = 1, \ldots, 5$, the number of hours, the reference mean price (from the power exchange EEX data for 2005-2006) and the slope of the inverse demand function.

Table 1: Load periods: hours, price and demand function

		h_j (hours)	p_j (€/MWh)	b_j (M.€/(TWh)^2)
base hours	$j = 1$	3504	30	-0.25
midbase1	$j = 2$	1752	43	-0.55
midbase2	$j = 3$	1752	54	-0.63
peak hours	$j = 4$	1664	84	-0.86
extreme peak	$j = 5$	88	233	-42.72

3.2 Initial generation capacities and technologies

Initial capacities are based on five technologies : nuclear plant (20.3 GW), brown coal conventional plant (19 GW), hard coal conventional (24.5 GW), combined cycle gas turbine or CCGT (16.1 GW) and 'peakers' (4.4 GW). An availability factor that depends on the load period is introduced in the production constraints for each technology.

The initial capacities are split between five producers: two large players, player 1 (RWE) and player 2 (Eon) with 29% and 24% of the available capacities respectively; two smaller players, player 3 (Vattenfall) and player 4 (EnBW) (17% and 11% respectively); the fifth player is a non-strategic fringe corresponding to the *Stadtwerke* and other producers of the German market (19% of capacities). Producers have different portfolios of technologies: player 2 (Eon) and player 4 (EnBW) have more than 40% of nuclear power plants, while player 1 (RWE) and player 3 (Vattenfall) have more than 60% of brown coal and hard coal power plants. A detailed table[9] can be found in Ellersdorfer (2005) .

Phasing out of existing capacities will take place progressively over future periods. Phasing out of nuclear capacities will reach 1.2 GW/yr by 2020. Hard coal and brown coal capacities will be shut down progressively at the initial rate of 0.6 GW/yr, speeding up to 1.2 GW/yr by 2020. In our simulations of the German market, nuclear has been ruled out as an option for future investment, consistent with available information on Germany's energy future. We also rule out investment in brown coal which depends highly on subvention policies. Hence, only coal powerplants, CCGT and peakers are available as new investments.

We also test the impact of climate policy on the economics of the respective technologies. The variable costs of the fossil fuel technologies depend on the

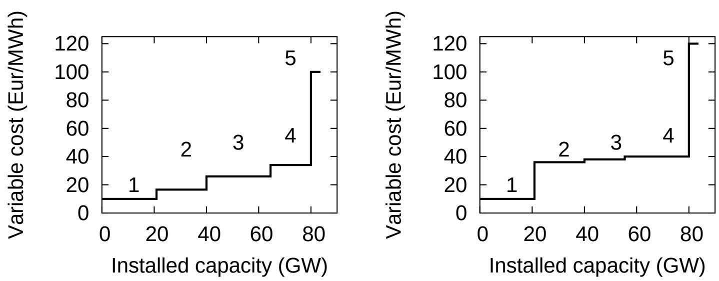
[9] Our fi gures differ only marginally from this source.

market price of tradable CO_2 allowances. We use two assumptions for our simulations. The first is a fixed price of 20€ per ton of CO_2, in line with the price of carbon futures quoted by EEX for 2008–2012 on June 19th, 2006.However, we also considered a case where carbon emissions have a zero opportunity cost. The impact of this assumption on the merit order and on the variable cost curve of the industry (with initial capacities) are shown in table 2 and on Figure 2. When

Table 2: Merit orders and price of carbon

CO_2 Quota price	1	2	3	4	5
0€/t	nuclear	brown coal	hard coal	CCGT	peakers
20€/t	nuclear	brown coal	CCGT	hard coal	peakers

Figure 2: Marginal cost curve of the industry
With 0 €/tCO2 (left panel) and 20 €/tCO2 (right panel)
Roman numbers refer to the positions in the merit order given in Table 2



the opportunity cost of CO_2 emissions is 20 €/t, an immediate consequence is that CCGTs have not only lower initial investment costs compared tocoal plants, but also lower variable costs. Therefore no investment is directed to coal power generation under this scenario.

3.3 Objective function

The random profit of player i in one year of a time step t is defined by i's sales minus his production and investments costs

$$\pi_{it} = \sum_j \sum_\ell \left(p_{jt}(Q_{jt}, \gamma_t) - C_\ell\right) h_j q_{i\ell jt}(\gamma_t) - \sum_\ell \kappa_\ell I_{i\ell t}(\gamma_t) \tag{8}$$

Where Q_{jt} is the power offered during period of load j, $Q_{jt}(\gamma_t) = \sum_i \sum_\ell q_{i\ell\, jt}(\gamma_t)$, κ_ℓ is the investment cost of technology ℓ (including fixed costs) and C_ℓ is the variable cost of production of technology ℓ.

The objective function is the total present-value expected profit Π_i referred to in section 2.2 and is simply defined[10] by $\mathbb{E} \sum_t \frac{\pi_{it}}{(1+\rho)^t}$, whith the discount rate $\rho = 8\%$.

4 RESULTS AND ANALYSIS

Three different simulations were computed. All simulations assume four strategic players and a competitive fringe. The competitive fringe is limited in its investment decisions and simply replaces capacities that are retired from the system. The two first simulations reflect the game described in the above sections and are distinguished by the carbon price assumed (20 € or 0 €/tCO_2), which affects the variable costs of production of the four non-nuclear technologies. The objective of running these two simulations is to show the impact of different cost structures on the investment decisions of the respective players. In the third simulation, the game is modified and an additional constraint is imposed on the largest player such that it must increase productions in the second game.

4.1 Restriction in capacity development and symmetrisation

In the game described in the above sections, one can notice that during a given load period j, producers set their quantities so as to maximise profits during this load period in any s.o.w. As a consequence, a strategic player i will produce with technology ℓ during the load period j only if (random parameter and time subscript t have been omitted):

$$C_\ell \leq p_j + \left(\frac{\partial p_j}{\partial Q_j}\right) \sum_\ell q_{ij\ell},$$

where the price p_j is a function of the total energy produced ($Q_j = \sum_{i',\ell} q_{i'j\ell}$), see Eq. 4. The right hand side (rhs) of the equation defines the marginal revenue of player i. It is defined as the market price p net from the marginal loss $p' \sum_\ell q_{i\ell}$ that player i would incur from depressing the price by increasing marginally the amount of energy he offers on the market. The last technology that satisfies the above equation for the player i represents the *marginal technology* for player i. When the inequality is strict, the player i will operate technology ℓ at full capacity and

[10] The objective function also includes a valuation of the existing equipements at the end of the time-horizon of the model. This valuation is made according to their vintages.

make profits from operating his last unit of technology ℓ. When there is equality between the lhs and the rhs, he may put only a fraction of his available capacity of this technology in operation and the last operating unit of technology ℓ will yield zero profit. As for the fringe, it will produce at full capacity with technology ℓ as long as $C_\ell < p_j$ and will operate partially if $C_\ell = p_j$.

During a load period j, the marginal losses of the players (last term in the rhs of the above equation) are different in proportion to the production of each player during this load period ($\sum_\ell q_{ij\ell}$). Hence, the larger the production of a player, the larger his marginal loss and rationale for production restriction. Consequently, when a player has a relatively large portfolio with low variable costs technologies like nuclear or brown coal that operates at full capacity during most load periods, he does not operate higher cost technologies. Other player with a different portfolio mix may, however, find rationale to operate such technologies. In this game, the competitive positions of the players are determined by their initial and evolving portfolio of equipement with different sizes and structure of fixed/variable costs.

4.1.1 Simulation results with a carbon price of 20 €/tCO$_2$

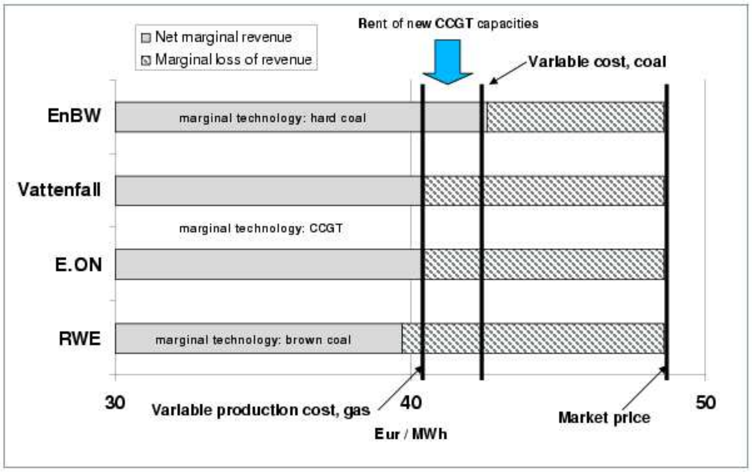
The smaller player, Player 4, is the first to commit to investment in the second-time step (2007–2008) with new CCGT capacities[11] beginning production two time-steps later (2011–2012). Figure 3 illustrates the incentive to investment for player 4 as well as the production restriction behaviour by the players during midbase1 ($j = 2$) in the first year of production of the new capacities (2011). The market price is 48.6 €/MWh, which is above the variable cost of CCGT (40.4 €/MWh) and the variable cost of coal generation (42.6 €/MWh).

Even though the market price is above the variable cost of production with CCGTs, the largest player (Player 1/RWE) does not offer production from his existing CCGTs during this load period: due to his large production from brown coal and nuclear powerplants, his marginal loss $p'(q_{\ell=1} + q_{\ell=2})$ drives his marginal revenue under the variable cost of CCGT. Therefore the sale of an additional MWh produced with CCGT would yield less direct profits than it would decrease the profits made from the sale of nuclear and brown coal productions.

For Players 2 and 3 (Eon and Vattenfall), production from nuclear and brown coal powerplants is important but smaller and not to the point where the marginal loss on the profits of this production would set the marginal revenue under CCGT variable cost. Hence, they also generate with their CCGTs but not at full

[11] The size of the added capacities depends on the realization of the random growth observed between 2005–2006 and 2007–2008.

Figure 3: Price, variable cost, and marginal revenue of oligopolistic players
Time step=yr 2011, load period $j = 2$. Price and variable costs refer to the consumption of a MWh, before distribution losses.
The data shown are for a medium growth path among the 8 growth paths that have unfolded in 2011.



capacity: they limit their production to the level where the marginal loss of revenue on all their production in midbase1 (nuclear, brown coal, CCGT) exactly compensates for the variable cost of production with a CCGT plant. Identical reasonning explains why neither player 1, 2 or 3 offers production from hard coal powerplants even though the market price is above the cost of hard coal generation.

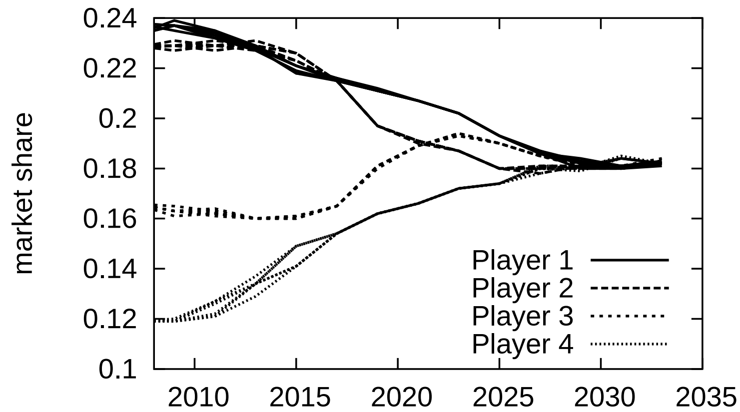
Finally[12], the fourth player, which has less initial capacities, uses its coal generation plants as the marginal technology, while it produces with all his CCGT capacities. The difference between Player 4's marginal revenue and the variable cost of CCGT production is the rent obtained by the last unit of CCGT capacity during midbase1. When this rent is large enough, cumulated on all load periods and future time-steps of the probability-weighted scenarios, investment in new CCGTs capacities can be made.

As a consequence, Player 4 is the first to perceive some advantages to invest and will do so as long as its marginal revenue remains higher than those of its competitors. Therefore, the industry tends to become symmetrical over time as shown by the market shares displayed in Figure 4. This tendency would not be

[12] In the game we describe, the fringe of *Stadtwerke* is assumed to make a competitive offer of its capacities (mainly gas powerplants) but remains limited in investment. Its investment cannot do more than to compensate for the retirement of its own capacities.

apparent with a shorter 10 years horizon. Large players also invest in capacities

Figure 4: Evolution of the market shares of the strategic players.
Market shares are displayed for the six demand scenarios that have a long-term reference growth rate of 0.5% (see Figure 1)



but do not begin to do so before the second half of the next decade. Before that, they restrict the quantities produced, leaving to smaller players the opportunity to invest first and grow. Then, the whole of competitors restrict the development of capacities available for production.

4.1.2 Simulation results with carbon price of 0 €

With a zero cost of carbon emissions, the broad evolution to symmetry holds again, but there is more diversity in the investment choices. Indeed in this context, the variable cost of coal generation is less than the variable cost of CCGT. Hence, coal powerplant that are expensive to invest in will be chosen to operate during a large number of hours and serve all load periods from $j = 1$ (base) to $j = 5$ (extreme peak), while less expensive CCGTs will be invested in to serve the additional demand that occurs during the hours of higher load periods from midbase1 to extreme peak. This is made clear from Table 3 which shows the annualized full cost of new coal powerplants and CCGTs depending on the number of load periods during which they operate. Full costs include the annualized investment cost, the fixed costs and the sum of variable operation costs which depends on the number of hours of operation.

Here again player 4 is the first to invest. Investment begins in the first

Table 3: Annualized full costs (€/MWh) depending on the operation
Availability factors are taken into account.

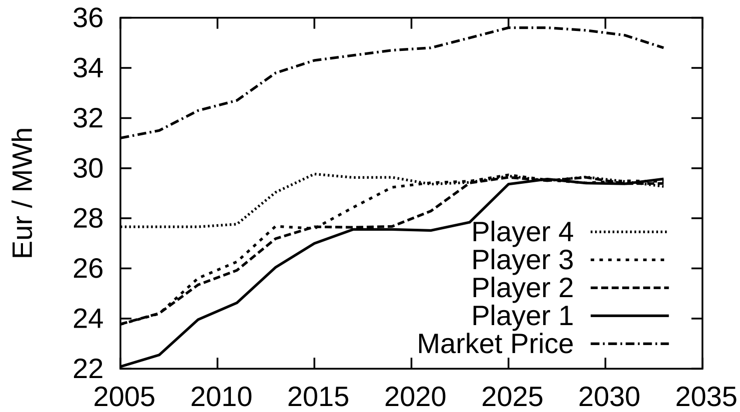
Load periods of operation	Coal powerplants	CCGTs
1–5: Base→ Ext. peak	40.6	42
2–5: Midbase1→ Ext. peak	50	47.4
3–5: Midbase2→ Ext. peak	61.1	54
4–5: Peak→ Ext. peak	92.9	74.1
5: Extreme peak	1338	832

time step (2005) and are made in CCGTs capacities. Only from year 2011 on does Player 4 also invest in hard coal capacities (production beginning in 2015), while at that time Player 3 begins investment but sticks to CCGTs.

As for CCGTs, investment in coal powerplants is triggered jointly by the retirement of existing capacities across the industry and the production restriction from existing capacities. Figure 5 gives some additional explanations: during the first time-steps, the phasing-out of nuclear and brown coal capacities results in a decrease of production while the demand curve tends to rise and pushes the price higher. Players 1–3 therefore see a diminution of their marginal loss of revenue and a corresponding rise of their marginal revenue (see Figure 5) but not immediately to the point where they begin production with coal during load period $j = 1$. This point is attained only when their marginal revenue compensates for the variable cost of coal production, 27.7€/MWh, namely by 2013 for player 3, 2015 for player 2 and 2017 player 1.

For player 4 who has less nuclear and brown capacities than the other players, the wedge between the cost of coal generation and marginal revenues in large enough already in the starting year and he offers hard coal generation in $j = 1$. But not all his capacities are offered in the first year. As nuclear and brown coal production by all players recedes, player 4 increases the production in $j = 1$ from his existing available hard coal capacities and maintains his marginal revenue constant while the price increases. From the year when all hard coal capacities of player 4 are offered in $j = 1$, marginal revenue soars above the variable cost of coal generation and yields a net rent per MWh for the marginal coal capacity producing at full capacity. The rent ultimately reaches the point where, when compounded with the rents gained during the other load periods $j = 2 \ldots 5$, it is sufficient to balance the investment and fixed cost of new coal capacities. Marginal revenue of player 4 stabilizes around this level. The same happens in turn to each of the player.

Figure 5: Marginal revenue in load period $j = 1$ along the highest growth scenario



4.2 Exogenous commitment and preservation of market shares

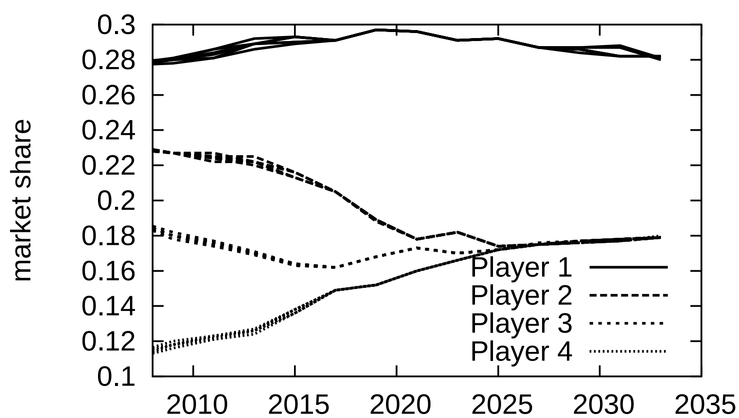
In the preceding section, results emphasized how small players grow and reduce market share of larger players, which in turn leads to the symmetrization of the industry. This contrasts with the analysis of Spence (1977) and Dixit (1980) that show that the incumbent firm may use its Stackelberg-leadership to expand its capacities in the first period, so that it will deter new firms to enter in the second period. In our oligopolistic model, we assume no player is endowed with an exogenous leadership and players draw their decisions simultaneously. We also note, that when firms are initially identical, persistent endogenous asymmetries are not easy to obtain, especially within the Cournot setting. Besanko and Doraszelski (2004) consider a infinite-horizon dynamic model with capacity accumulation and show that quantity competition leads to an industry structure of equal-sized firms[13]. One could expect, however, that in a multi-stage model, quantity competition and simultaneous investment decisions at each stage would not necessarily suppress any ability to deter investment when firms are initially of different size and have different initial cost structures (due to difference in technology mix). Yet in a one-stage decision framework, this ability does not materialize.

[13] Endogenous asymmetries require price competition to arise in the model. von der Fehr and Harbord (1997) had also obtained endogenous asymmetries (one large firm and $N-1$ equal-sized) in a two-stage model, where in the second-stage firms submit offer prices and a unique market price is determined from them (all capacities that are called receive the same price unlike in standard price competition).

We give an illustration of this ability in the following simulation where an exogenous constraint has been added to the game described in section 2.2. We now assume that the Player 1 (RWE) has committed (is constrained) to produce more than its Nash-equilibrium quantity in the game described in section 2.2. Specifically, we impose a constraint thatquantity produced by Player 1 (RWE) in any year t and s.o.w. to be above its latter equilibrium quantity plus the quantity corresponding to the increase in market share by Player 4 (EnBW).

As a result, it can be observed in Figure 6 that Player1 preserves its market share[14], while the rest of the industry tends to symmetrisation, as in section 4.1. More significantly, at the equilibrium derived from this new game, the present-value profits of Player 1 are higher than at the equilibrium without the commitment constraint. However, it is questionable whether Player 1 can credibly commit to such production levels.

Figure 6: Evolution of Market shares with commitment by player 1.
A 0 €/tCO_2 opportunity cost of emissions has been assumed.



[14]In this case we used a 0 € opportunity cost per ton of carbon emissions. This explains why market-shares in the first year already differ from those in Figure 3. Results for the 0 €/tCO_2 reference simulation are available from the corresponding author.

5 CONCLUSION

This study has attempted to highlight some aspects of the interdependence of long-term investments and production behaviours of oligopolistic electricity producers. Our approach, based on a numerical model of oligopolistic competition, allows some key features of the electricity market, previously neglected by theoretical two-stage oligopoly models, to be taken into account. For example, we model long-term horizons for the cost-recovery of power plants as well as uncertainty of future demand growth, load duration curve and technologies portfolio.

The exercice draws attention on the possible behaviour of production restriction and of delayed investment by dominant players; this behaviour results in accommodating entry of minor players and tends to drive the industry towards a long-term symmetrisation of the market shares. Hence, large players may wish to carefully design investment strategies in order to preserve their market shares and profits.

With the modelling framework we have built, several further extensions and improvements can be envisaged. In particular, it might be useful to take into account, ex ante levels of vertical integration of the producers, namely their commitment to supply small consumers at a predetermined exogenous retail price. This would tend to secure investments and reduce the exercise of market power on the spot market[15]. Finally, instead of representing uncertainty on the future growth of demand, an interesting application would be to consider other risks that affect decisions in the long-run, in particular the uncertainty of the future fuel and CO_2 allowance prices. These could impact technology choices and the variance of profits to a significant degree.

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APPENDIX

Conditions for a solution of the theoretical model in section 2.1

For the two-stage game described in section 2.1, a closed-loop Nash equilibrium $(I^{\#}, a^{\#})$ verifies for all admissible (I, a) :

$$\Pi_1(I^{\#}, a^{\#}(I^{\#})) \geq \Pi_1(I_1, I_2^{\#}, \ldots, I_N^{\#}, a_1(I_1, I_2^{\#}, \ldots, I_N^{\#}), a_2^{\#}(I_1, I_2^{\#}, \ldots, I_N^{\#}), \ldots, a_N^{\#}(I_1, I_2^{\#}, \ldots, I_N^{\#}))$$

$$\Pi_2(I^{\#}, a^{\#}(I^{\#})) \geq \Pi_2(I_1^{\#}, I_2, \ldots, I_N^{\#}, a_1^{\#}(I_1^{\#}, I_2, \ldots, I_N^{\#}), a_2(I_1^{\#}, I_2, \ldots, I_N^{\#}), \ldots, a_N^{\#}(I_1^{\#}, I_2, \ldots, I_N^{\#}))$$

$$\ldots$$

$$\Pi_N(I^{\#}, a^{\#}(I^{\#})) \geq \Pi_N(I_1^{\#}, I_2^{\#}, \ldots, I_N, a_1^{\#}(I_1^{\#}, I_2^{\#}, \ldots, I_N), a_2^{\#}(I_1^{\#}, I_2^{\#}, \ldots, I_N), \ldots, a_N(I_1^{\#}, I_2^{\#}, \ldots, I_N))$$

Further, a pure feedback Nash equilibrium solution for the two-stage game verifies for all $I = (I_1, \ldots, I_N)$,

$$\Pi_1(I, a^{\#}(I)) \geq \Pi_1(I, a_1(I), a_2^{\#}(I), \ldots, a_N^{\#}(I))$$

$$\Pi_2(I, a^{\#}(I)) \geq \Pi_2(I, a_1^{\#}(I), a_2(I), \ldots, a_N^{\#}(I))$$

$$\ldots$$

$$\Pi_N(I, a^{\#}(I)) \geq \Pi_N(I, a_1^{\#}(I), a_2^{\#}(I), \ldots, a_N(I))$$

Such an equilibrium corresponds to a two-stage decision making process: second-period actions are chosen on the basis of the observed first-period actions. First-period actions are chosen with consideration of how second-period actions will be made. The solution can be obtained by recursive resolutions:

- First, solve the offer competition game, for any given first period vector of actions I.

$$a_i^{\#}(I) \in argmax_{a_i} \Pi_i(I, a_1^{\#}(I), \ldots, a_i, \ldots, a_N^{\#}(I))$$

- Second, solve the first-period action game (I = investment and, if relevant, retail price)

$$I_i^{\#} \in argmax_{I_i} \Pi_i(I_1^{\#}, \dots, I_i, \dots, I_N^{\#}, a^{\#}(I_1^{\#}, \dots, I_i, \dots, I_N^{\#}))$$

An open-loop Nash equilibrium $(I^\star, a^\star)$ verifies for all admissible (I, a) :

$$\begin{aligned}
\Pi_1(I^\star, a^\star) &\geq \Pi_1(I_1, I_2^\star, \dots, I_N^\star, a_1, a_2^\star, \dots, a_N^\star) \\
\Pi_2(I^\star, a^\star) &\geq \Pi_2(I_1^\star, I_2, \dots, I_N^\star, a_1^\star, a_2, \dots, a_N^\star) \\
&\dots \\
\Pi_N(I^\star, a^\star) &\geq \Pi_2(I_1^\star, I_2^\star, \dots, I_N, a_1^\star, a_2^\star, \dots, a_N)
\end{aligned}$$

Note that, in the open-loop equilibrium, even though the knowledge of what has actually been done before does not modify second-period actions $a_i^\star(s)$ taken, second period actions are dynamically coherent with first-period actions, in the sense that $a_i^\star = a_i^{\#}(I^\star)$. However, first-period actions $I^\star$ in the open-loop equilibrium may differ from those in the closed-loop equilibrium, $I^{\#}$.