An Agent-based model to analyse the long-term development of the German electricity system

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Abstract

In this paper, we present an agent-based simulation model of the long-term development of the German electricity market. The model includes a day-ahead spot market and forward market module for the simulation of long term price developments, and an investment decision module. This article gives a detailed model description and presents first results.

Key words: agent-based simulation, energy system modeling, electricity market modeling, investment planning

1 Overview

The German electricity sector has undergone considerable changes throughout the past few years. Main developments are the liberalisation of electricity markets and the European CO_2 emissions trading scheme that started in 2005. These developments challenge the electricity generating companies to deal with new uncertainties like high volatile electricity and CO_2-certificate prices. The phase-out of nuclear power plants in Germany until approximately 2025 and the fact that many coal and gas fired power plants will reach the end of their technical lifetime in the next years leads to a high investment need for new power plants. In the next 20 years the estimated need for new power plants in Germany is about 40 GW (Jäger, 2005). Do enough incentives for power plant investments exist? Will adequacy, the long-term security of electricity systems, be ensured in a liberalised power market? In this paper, we present an agent-based model for the long-term simulation of the German electricity market to analyse these questions.

2 Methodology

In this chapter, the methods and theory used in the simulation model, the agent based modeling approach and aspects of investment planning are briefly introduced.

2.1 Agent-based modeling

Traditional energy system models are often based on a central optimization routine (Enzensberger, 2003). Although working quite well in regulated electricity markets, it is not clear whether these models are adequate to simulate liberalised markets with higher price risks, uncertainties and possibly different strategies of the market players. A promising and novel approach for the scientific analysis of dynamic systems is the field of agent-based simulation (Tesfatsion, 2002). Market players like electricity generating companies or operators of renewable energy plants can be modelled as one ore more software units called agents. The behaviour of these agents can be specified freely. The research field of agent-based simulation is based on several disciplines as economy, game theory and software engineering (Wooldridge, 2002). Though there are several definitions of the term agent, the following characterisation is quoted relatively often (Wooldridge, 1995): agents are autonomous (able to operate on their own), social (able to interact with other agents), reactive (able to respond to a changing environment) and pro-active (able to act on their own initiative in order to reach envisaged goals).

2.2 Investments in liberalised electricity markets

Investment in electricity markets are characterized by high uncertainties and irreversibilities (Müller, 2005). Uncertainties mainly are caused by uncertain cash-flows due volatile electricity, fuel and certificate prices, which determine the returns. A power plant usually has a long amortisation period, so investment decisions are highly irreversible.

In former times, power plants with the best net present value were built. Under the new environment in liberalised power markets, plants are only built if enough profits are likely in an uncertain environment. This might lead to the fact that power plants will not be built if electricity prices are too low even if there is a need in sense of a demand/supply perspective.

In theory, several ways of ensuring adequacy are known. According to (Oren, 2000) adequacy can be seen as long-term system security, as the ability of a system to meet aggregate power and energy requirement of all consumers at all times. In an ideal competitive market with continuously varying electricity prices payments to inframarginal generators should cover capacity costs. Direct capacity payments are another possibility for an incentive system for power plant investments.

3 Model description

This chapter seeks to provide a detailed description of the developed model. An overview of some parts of the model (Genoese et. al, 2005) is given in Fig. 1. The model simulates the German electricity markets and has two main timescales. There is a module to simulate short-term developments, which consists of several markets like a day-ahead electricity market, and a long-term simulation module, which simulates capacity expansion decisions of electricity suppliers, the development of renewable capacity and electricity demand. Both parts, the long-term capacity decision and the short-term markets, interact.

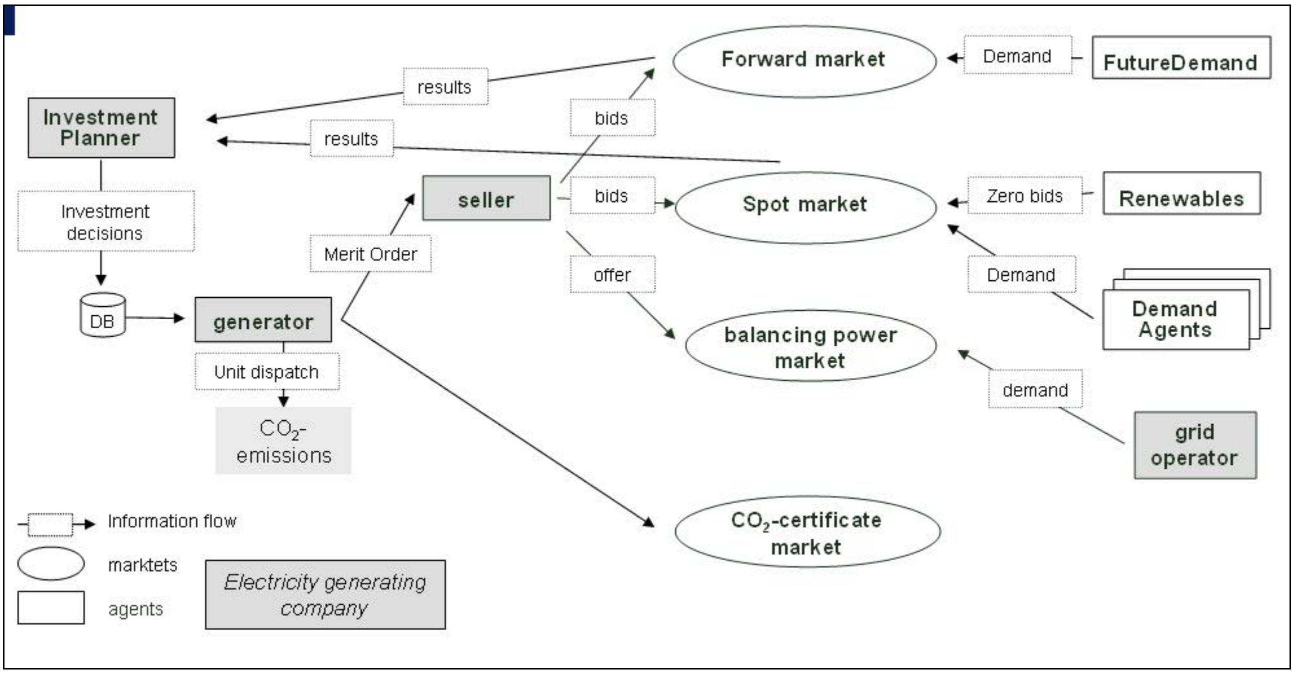

Fig. 1: Model overview (based on Genoese et. al. 2005)

This model is conceived as long-term forecast and decision support system for investment decisions, and also gives a good estimation of the development of electricity prices. Every relevant player in the electricity market is represented by one ore more agents, i.e. an electricity generating company is represented by a generator, a seller, a grid operator and an investment planner.

3.1 Data input

The model is linked to several databases containing relevant German power plant information, detailed hourly demand data and load data of renewable energy. This data is used in the fundamental decision algorithms of the agents and is needed to provide realistic results. The power plant data can be used as static input (in this case the power plant portfolio remains constant over the simulation), it can be used a predefined data set representing the future development of the energy system, or the capacity development can be computed endogenous within the model.

3.2 Short term electricity and certificate markets

First, the short-term part are explained. Realistic electricity prices, especially high price spikes, are very important for capacity decisions, because they are the main investment incentive in liberalised markets. So it is necessary to model electricity markets in a very detailed way in order to generate realistic market results. In the short-term-perspective a day-ahead spot market is simulated, it is assumed that the whole electricity consumption is traded on a daily spot market. *Sellers* of electricity offer power plant capacities of their company (their *generators*), considering variable costs, restart costs and mark-ups depending on the demand/supply ratio in their bidding price. The bidder's behaviour will be explained later.

On a second market for electricity, the balancing power market, power plant capacities that have not been sold in the daily auction can be offered. It is assumed that there is only one balancing power market, and the market clearing takes place after the results of the day-ahead spot market are known. The demand for balancing power can be set in the agent *gridoperator*. For future years it is set depending on installed wind capacity according to (Dena, 2005).

A third electricity market is the forward market. On this market, sellers can bid capacities which will be available five-years later. So capacities in construction are included if they will be completed in less than five years. Not included are capacities which will be mothballed or shut down. The future demand mainly depends on the assumed demand growth. The results of this market do not interact with the spot market results, but show a price expectation of the agents, which is important for investment decisions in the model.

The certificate market can be integrated from the beginning of 2005. The unit dispatch of the *generators* causes CO_2-emissions (which are balanced), the certificates needed can be bought on the market. Alternatively a price for CO_2-certificates can be set as a simulation parameter modifying the merit order curve of the generators. Every plant gets an initial allocation of CO_2-emission allowances. For the simulation runs of this paper the CO_2-market is deactivated in order to simplify the model.

3.3 Agent's behaviour on short-term markets

In this chapter, a short overview over the agents acting on the short-term markets described in the previous chapter is given. On the electricity supply side each of the major utilities is represented by a seller and a generator.

(a) Seller's behaviour

The supply side bidders, the agents of type Seller, can act in various ways on the market. A first algorithm creates bids based on variable costs of the power plants, without any strategic behaviour. A comparison of the model results of 2001 with the real market shows a good correlation with real market results of the European Energy Exchange (EEX) of 2001 in some parts of the price range. Very low prices above variable costs cannot be modeled as little as price peaks, which exceed the variable costs. This can be observed in Fig. 2, where the prices for two different spring weekdays are shown. On the left figure the model price (lines with squares) is too low compared to the EEX market price (line with circles); on the right figure the model price in some hours is too high.

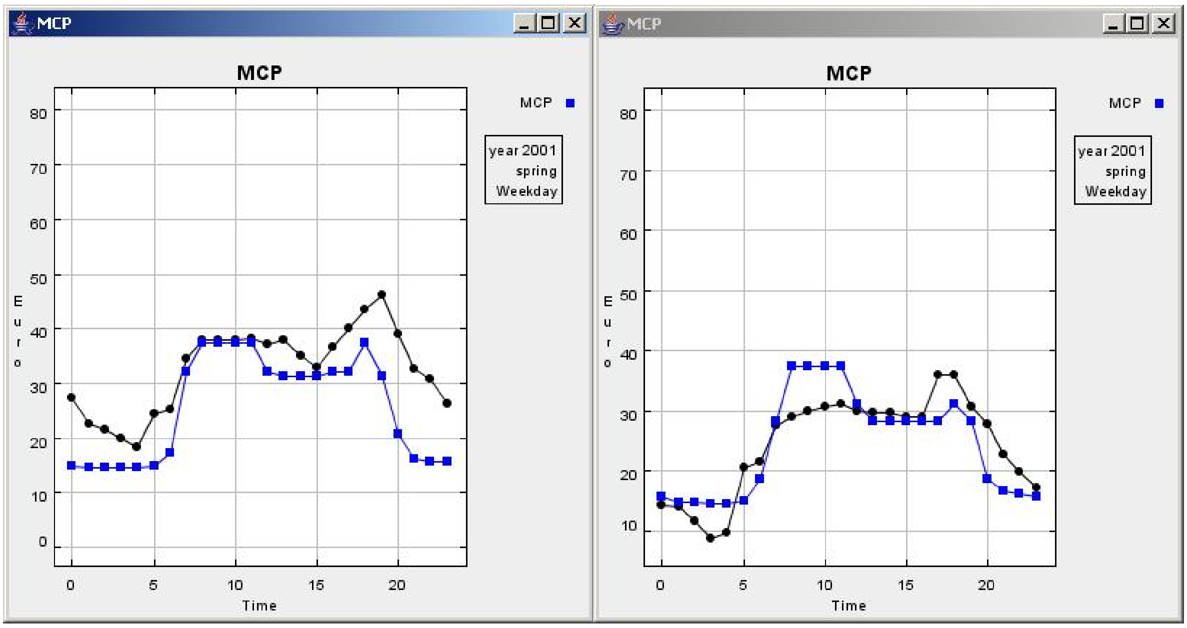

Fig. 2: Results of the simple bidding behaviour

These results indicate that in some hours other parameters have to be considered. I.e. considering avoidable costs in the bids better results can be obtained. To avoid a restart of a power plant, the bid can reduced by the restart costs of a power plant unit. These restart costs are allocated on hours in which the variable costs of the unit are higher than the expected spot price. The bid is calculated as follows:

$$p_{bid} = \max(c_v - \frac{c_s}{T}, 0) \qquad \text{(Equation 1: Reduced bidding price)}$$

p_{bid} is the bid price,

c_v are the variable costs,

c_s are start-up costs for a specific power plant,

T is the time interval, where the variable costs are expected to be higher than the spot market price of electricity.

The expected day-ahead spot price is the intersection point of the German merit order curve and the forecasted demand.

Start-Up costs can also be considered in the bidder's behaviour. The bidding price of gas and oil turbines can be modified as follows:

$$p_{bid} = c_v + \frac{c_s}{T} \qquad \text{(Equation 2: Increased bidding price)}$$

p_{bid} is the bid price,

c_v are the variable costs,

c_s are start-up costs for a specific power plant,

T is the time interval, where the variable costs of the considered plant are expected to be lower than the spot market price of electricity.

A detailed statistical discussion of the results of these modifications can be found in (Sensfuß and Genoese, 2006).

An additional modification of the bidding algorithm is a fixed costs mark-up. This mark-up is added on the bids depending on the demand/supply ratio. The higher this ratio is, the more scarcity is in the system, and the bidder can bid a so called inframarginal bid. Thisbidding behaviour can create additional income for the investments on a peak load power plant, for example. In a sample simulation run this mark up has the effect which can be seen on Figure 3. In this figure, the spot market results of the EEX and the model results for the same year are shown. In 2001, in few hours very high prices (up to 998€) can be observed. Such prices can hardly be explained, so prices above 150 € are filtered out. The mark-ups are shown in Figure 4 (taken from (Grobbel, 1999) and own computations), the mark-up is the share of the fixed costs and depends on the ratio of the supply (minus a reserve factor) and the demand.

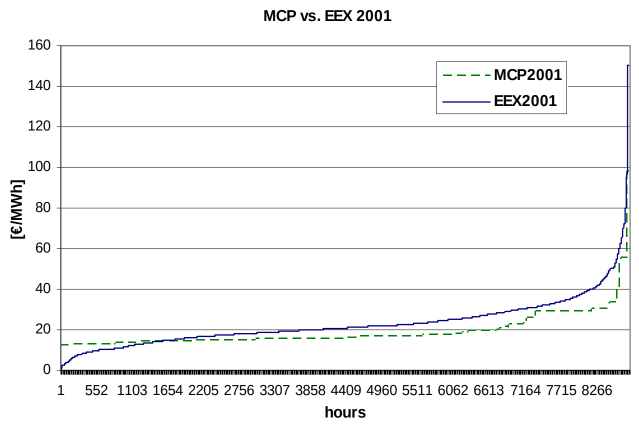

Fig. 3: price curve with mark-ups

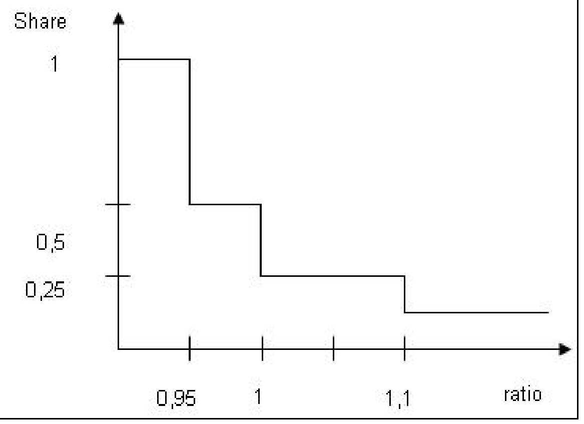

Fig. 4: mark-ups shares

(b) Demand side and renewable agents

On the demand side, the *Buyers* of electricity represent a non-elastic demand. The load profiles of the demand side are based on VDEW load profiles. The total demand can be kept constant throughout the simulation; the second possibility is a scenario with growing electricity demand. For a more detailed explanation of the data applied see (Sensfuß and Genoese 2006). The renewables agents are endowed with load profiles based on wind speed measurements at typical locations (Sensfuß 2003).

3.4 Long term simulation of investment decisions

The agent investment planner, which is part of the player "electricity generating company" analyses the different given capacity options and decides, whether new power plants have to be build and of which type they are. For every relevant player (the major utilities), one agent exists. In Figure 5 the market prices of the PowerACE-model of the first five model years are shown (respectively the two indices PhelixBase and PhelixPeak). High price spikes are observable due to shut down of old power plants, if no new plants are built, which is the case in this simulation run. These price spikes can be seen as investment incentive for new capacities. Figure 5 shows this simplified coherence. Prices rise, if old power plants are shut down and no plants are built.

In Figure 6, one decision rule for the investment planning is shown. A power plant unit runs, as long as the expected prices are higher than the variable costs of that unit. The area where the market price exceeds the variable costs is needed as contribution to cover the fixed costs of that plant. These fixed costs have to be covered during the life time of a power plant. This is illustrated in Figure 6, where the market price and the variable costs of a power plant unit are shown. In that example, the power plant would run in about 4800 hours.

At the end of one year, this agent checks the endogenous market results of the past year, the spot market prices (day-ahead market) and the results of the future market. These price curves are ordered and for every capacity expansion option, the possible profit of this plant type is computed (see Figure 6). So the profits are computed as follows:

$$\sum_{t,(p_t - c_f - c_v > 0)} (p_t - c_f - c_v) \qquad \text{(Equation 3: profit)}$$

p_t is the price in hour t

c_f fuel costs in €/MWh

c_v variable costs

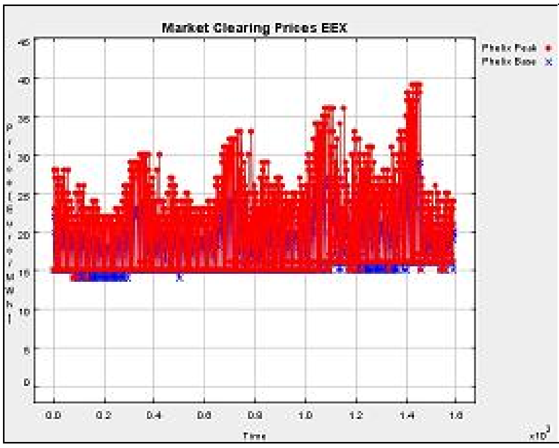

Fig. 5: price-trend in the model

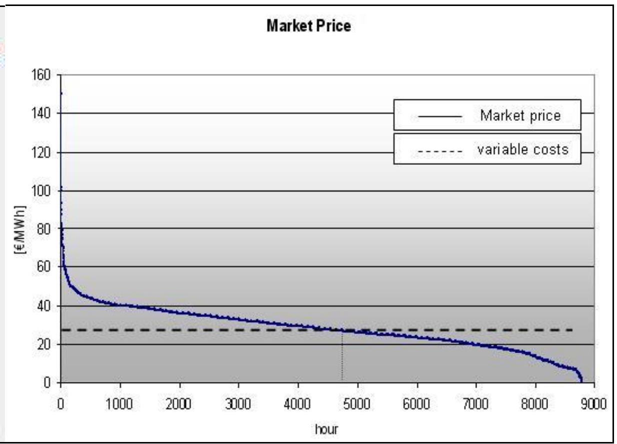

Fig. 6: unit commitment

In the next step, the same calculation is based on forward prices.

The annuities of the investments are computed as follows:

$$A = I * \frac{q^n * i}{q^n - 1} \qquad \text{(Equation 4: computation of annuities)}$$

A is the annuity

I is the investment sum

n the years

i the interest rate,

q=1+*i*

The parameters *n* and *i* can be set in a parameter file, the default values are *i=9%* an *n=40 years*. If the profits according to equation 3 are higher than annuities and fixed costs of a power plant, the unit is assumed to be profitable and is built considering a construction period of 4 years. The forward price and the spot market price are weighted equally. Every profitable plant is built without any restriction. Mothballing is not considered, power plants that reach their technical lifetime (40 years) are shut down automatically in the model. If too many plants are built, the forward price decreases, and less plants are built in the future.

Selected capacity expansion options are shown in Table 1. Every option is available for each agent, except lignite power plants that are only available for the agents of the players *RWE* and *Vattenfall Europe*.

Table 1: selected capacity expansion options (based on (Enzensberger, 2003))

Fuel	Technology	Year	Unit size	Specific investment	fixed costs	variable costs	efficiency
			[$MW_{install}$]	[€/$kW_{install}$]	[€/(kW*a)]	[Cent/kWh_{elec}]	[%]
Natural gas	combined cycle power plants (small)	2005	300	410	14,5	0,05	58,5
	combined cycle power plants (large)	2005	800	400	14	0,05	59
	Gas turbine	2005	150	255	6	0,15	35
Coal	Sub critical	2005	700	750	36	0,15	42,5
	Supercritical	2005	700	825	36	0,15	46
Lignite	Sub critical	2005	900	900	38,5	0,2	40,5
	Supercritical	2005	900	950	38,5	0,2	44

Table 2 shows the fuel prices for some years of 2000-2010; they are needed for the computation of the forward price curve.

Table 2: Development of fuel prices

Name	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Uranium	4	4	4	4	4	4	4	4	4	4	4
Coal	5	6,54	5,48	5,75	6	6,35	6,35	6,45	6,57	6,66	6,76
Lignite	3,95	3,95	3,95	3,95	3,95	3,95	3,98	4	4,03	4,06	4,09
Oil	23,6	22,23	20,86	19,48	18,11	16,74	17	17,29	17,56	17,84	18,11
Natural Gas	11	11,90	12,81	13,71	14,62	15,52	15,81	16,1	16,38	16,67	16,96

In [€/MWh], transport costs included, based on (Enzensberger, 2003) and own calculations

4 Results

Two case studies are carried out for this paper. As first analysis step, the profitability of the given investment options (from table 1) is analysed with EEX-prices of the year 2002 and 2004 and various interest rates (6, 7, 8 and 9%). Results of the application of these spot market prices on the decision algorithm presented in chapter 3.4 (assuming constant prices) are shown in Figure 7 and Figure 8.

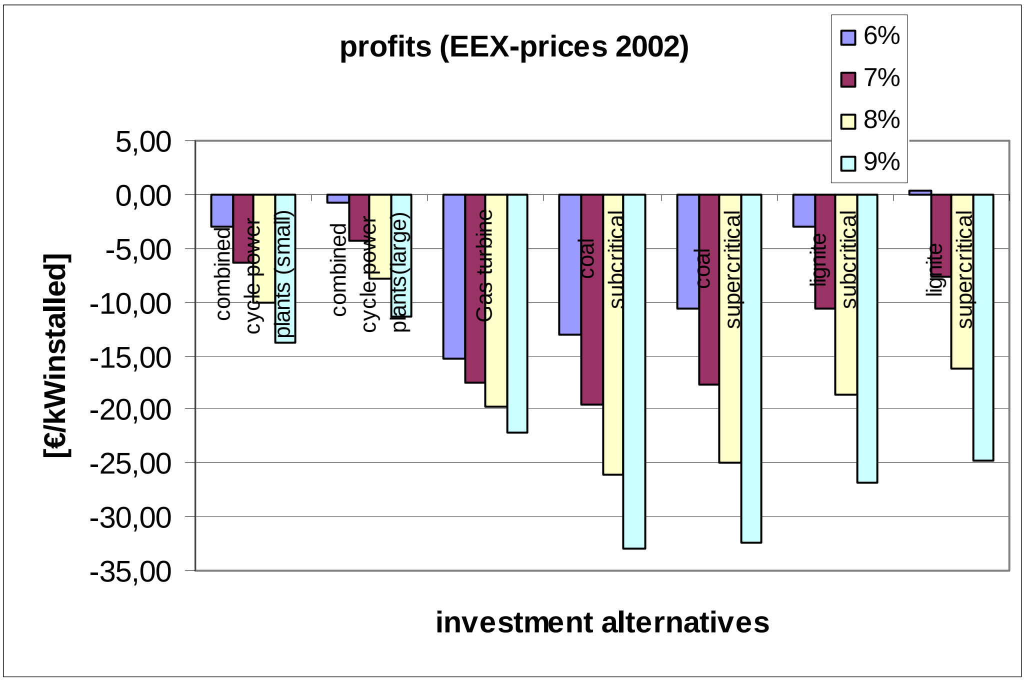

Fig. 7: profitability of investment options with EEX-prices of the year 2002

For the year 2002 EEX spot market prices have been too low to cover the fixed costs and the investment costs of new investments, for every considered interest rate.

The results for 2004 are different; all plant types from Table 1, except gas turbines, would have been profitable. Thereby lignite power plants would have been the most profitable units followed by the various coal-fired power plants and combined cycle power plants. These seem to be less advantageous because of the high gas price.

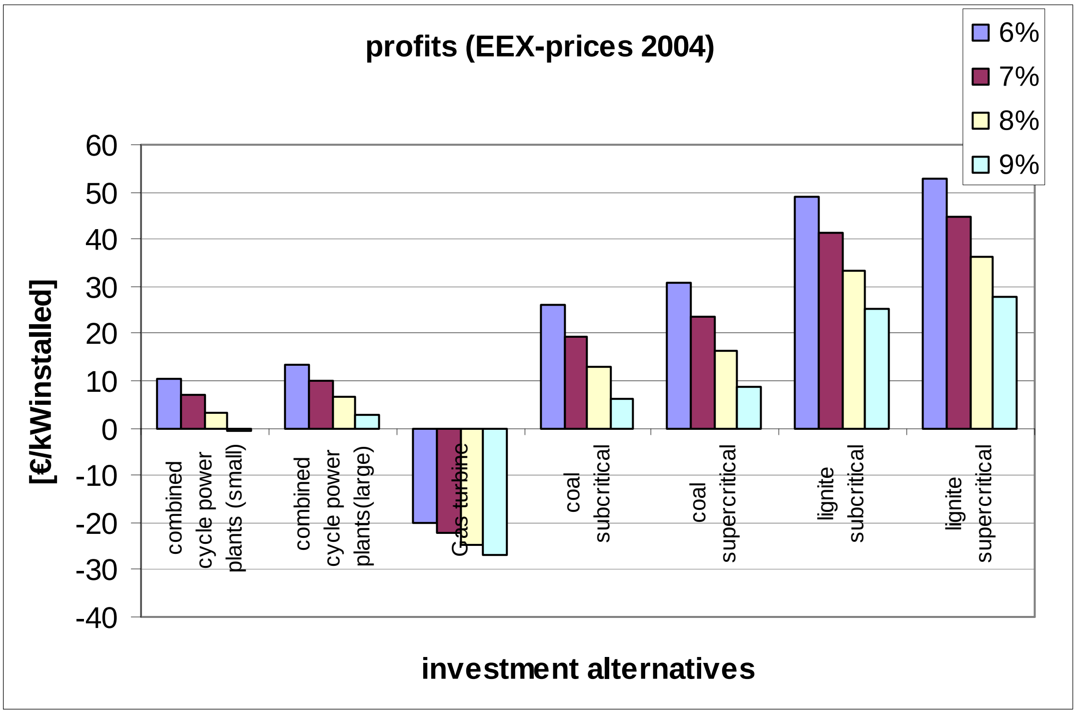

Fig. 8: profitability of investment options with EEX-prices 2004

In a second step, endogenous model prices are taken for the investment decision algorithm. Figure 9 shows the results of the investment decisions, on the left side the total new installed capacity, and on the right side the number of built units. Most of the power plants are built in 2006, 2016 and 2017.

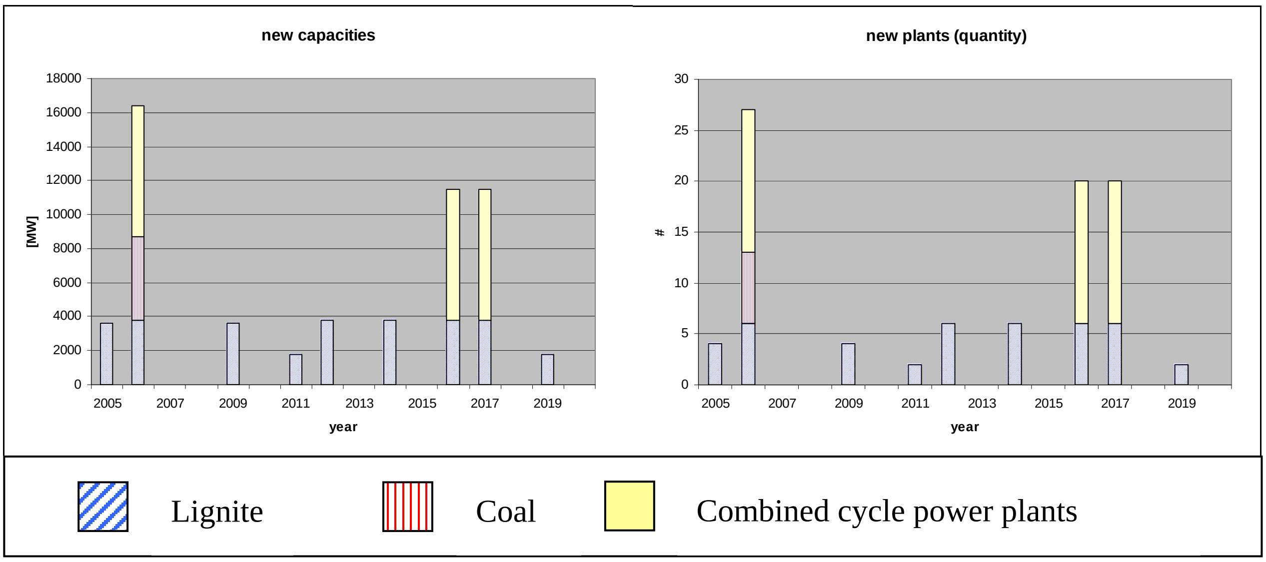

Fig. 9: New plants (left: total capacity and right: total number of new plants)

The preferred types are the lignite fired plants and the combined cycle power plants. In 2006 also 7 coal fired power plants are built. Again, in the model algorithm a construction time of 4 years is assumed, so the decision of building a plant has a lead time of 4 years . The construction of new plants concentrates in some years; the reason of this result is that investment decisions are made without any delay if plants are due for retirement. In reality, a player might decide to build a new plant some time later, maybe because he does not want to take the risk. Furthermore, capacities are shut down immediately, so prolongation of the lifetime is not possible.

Figure 10 shows the resulting power plant structure of Germany, the total installed capacity in the system including the new units shown in Figure 9. Hydro Units and other renewable electricity generation are not considered. Lignite fired and combined cycle power plants power plants are preferred, so the share of these technology increases. The German nuclear phase out agreement is not considered yet, although no new nuclear power plants are built.

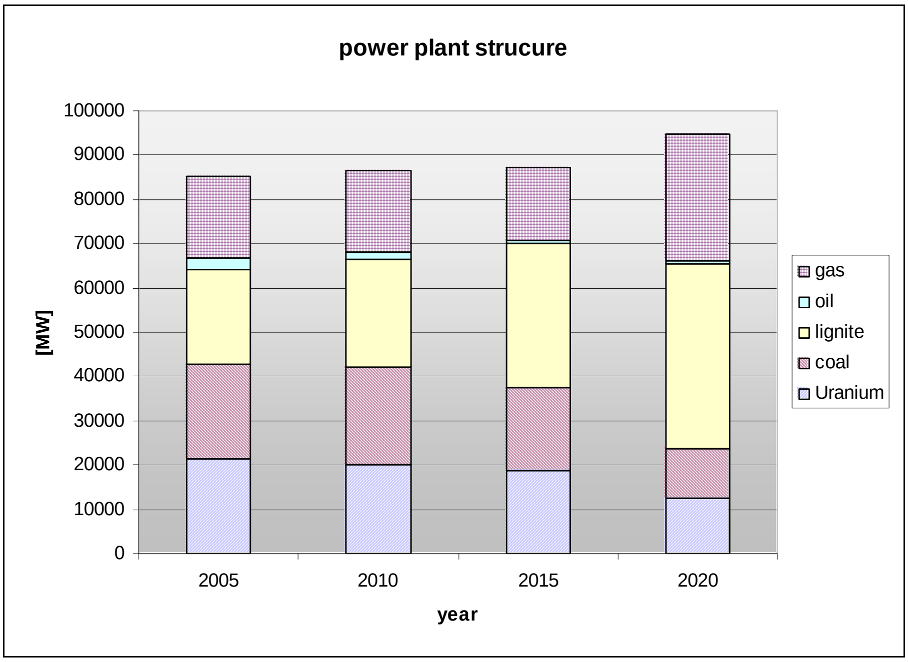

Fig. 10: Power plant structure of Germany

igure 11 shows the spot market prices of a long-term simulation run. Cycles are observable, high price spikes are followed by a relatively high capacity expansion and result in low electricity prices. Prices begin to rise again due to shut down of old capacities.

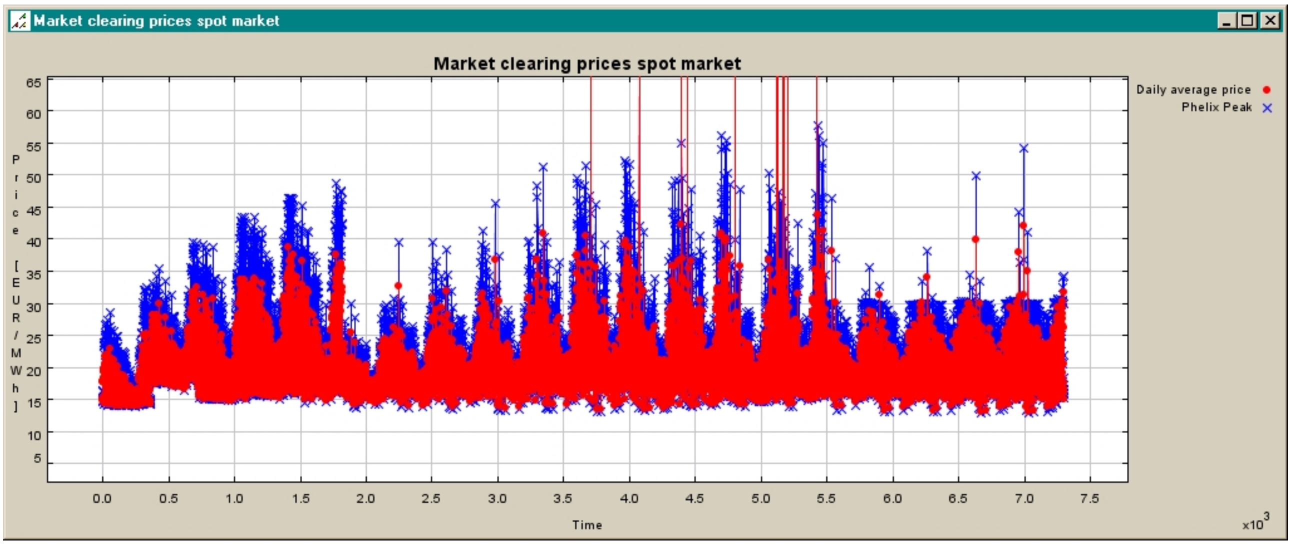

Fig. 11: Results of a long term simulation

5 Conclusions and outlook

The presented article presents work in progress. First results show that mainly lignite fired power plants and combined cycle power plants are built, which is conform to reality. In order to increase realism the decision rules of the algorithm have to be extended. The certificate market has not been considered in this simulation run, abatement obligation and allocation of new power plants with emission rights will have an effect on the investment decisions. Mothballing of power plant units has to be considered as an alternative option for complete deconstruction. Another future step is the integration a learning algorithm for the decision parameters applied in the algorithm for the capacity expansion decisions. Perfect foresight models usually do not show cycles of electricity prices, this might be an advantage of such an agent-based model.

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