Agent-based Simulation of the German and French Wholesale Electricity Markets

Recent Extensions of the PowerACE Model with Exemplary Applications

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Abstract: Given electricity markets' complexity, model-based analysis has proven to be a valuable tool for decision makers in related industries or politics. Among the different modelling techniques for electricity markets, agent-based modelling offers specific advantages. In this paper, the detailed agent-based simulation model for the wholesale electricity market, PowerACE, is presented with its latest extensions. The model integrates the short-term perspective of daily electricity trading and long-term capacity expansion planning. Various market elements are simulated including the day-ahead market as well as the coupling of different market areas with limited interconnection capacities. Strategic behaviour of the main supply-side agents is taken into account. The model has already been applied to various research questions regarding the development of electricity markets and the behaviour of market participants. In this contribution, exemplary results for the market coupling of the German and French wholesale electricity market are shown. In the future, due to the current developments in the electricity markets, the PowerACE modelling framework is to be extended by various aspects including the simulation of an intraday market and the integration of different aspects of uncertainty which becomes necessary given current developments in the electricity markets.

1 INTRODUCTION

Today's liberalized wholesale electricity markets are generally considered to be highly complex systems. This is due to, among other things, the specific characteristics of the commodity electricity (e.g. instantaneous balancing of supply and demand, limited storability) and the fact that electricity can only be transported by a transmission grid with limited capacities. Other factors that increase the complexity are the various interrelated markets where electricity or related products can be traded (e.g. day-ahead market, future market) and the influence of other volatile markets such as the market for carbon emission allowances.

One important aspect of electricity systems is the reliability which should be ensured at all times. In liberalized European markets electricity generation companies are not obliged to invest in new power plants. Consequently, electricity markets need to be designed in such a way that there are sufficient incentives for adequate investments. The currently often discussed concept to ensure reliability in Europe is called "energy only" because power plant operators generate their profits mainly from the produced energy but are not compensated for only providing generation capacity that ensures reliability.

In Germany and several other European countries the spot market for electricity, in particular the day-ahead market auctions organized by electricity exchanges, plays an important role as it provides a market place to sell or buy electricity and its price serves as a reference for other markets (e.g. future markets, bilateral contracts). In addition, reserve markets are implemented to ensure the short-term reliability of the electricity system.

Two important developments currently altering the economics of European electricity markets are the increasing electricity generation from renewable energy sources and the European market integration. While for a long time mainly nuclear, coal and oil power plants had been installed in Europe, governments have recognized the decarbonisation

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potential of the electricity sector and there has been a continuous trend to move towards renewables and gas. Specifically, the introduction of the European Union Emissions Trading System and the creation of various policy programs to support the use of renewable energy sources have contributed to this development.

However, the feed-in of electricity generated from photovoltaic and wind power poses challenges to the electricity markets in their current form because in comparison with thermal power plants the generation from these sources is neither projectable nor exactly predictable and typically enjoys a guaranteed feed-in and compensation, respectively. Consequently, operators of conventional power plants are faced with another source of uncertainty that needs to be considered within the unit commitment problem, where an optimal balance of demand and supply under the various technical constraints of the power plants is to be determined. After determining the day-ahead operation schedule, the intraday market, where electricity can be traded at short notice, offers a possibility to adjust the schedule based on updated information, e.g. forecast of renewable generation. The intraday market is likely to gain importance in the next years, as the generation from renewable energy sources is expected to further increase.

Another important development in the electricity market is that the current borders of the national markets are subject to change; there are ongoing efforts to achieve a single European market. One aspect thereof is the implementation of market-based mechanisms to allocate limited cross-border capacities between European countries. The Central Western Europe (CWE) Market Coupling between Germany, France, Belgium, the Netherlands and Luxemburg serves as one of the most prominent examples. Market coupling maximizes social welfare, leads to price convergence and helps to balance different supply and demand situation in the interconnected market areas. The integration of markets is a matter-of-fact, thus influencing market prices and profitability of power plants in Europe.

Given the electricity system's complexity the relevant actors rely on different types of models for decision support. For instance, models are used by regulatory entities to analyse questions related to market design which is necessary to guarantee system reliability on different levels. Similarly, generation companies rely on electricity market models, for example, in order to examine investment cases. Naturally, market changes need to be reflected appropriately in modelling techniques.

In this paper, the main elements of the detailed bottom-up agent-based simulation model PowerACE are described and current extensions to adjust the model to relevant electricity market developments are presented. The aims of this paper are to present a comprehensive overview of the PowerACE modelling framework for electricity markets and how it can be applied to different research questions.

The paper is organized as follows: section 2 provides a brief overview of the different types of electricity market models and shows the general suitability of agent-based simulation in the context of electricity markets. In section 3, the model's main elements with a focus on agents and markets are described. Exemplary results are presented in section 4. Finally, section 5 concludes with a summary and an outlook.

2 MODELS FOR ELECTRICITY MARKETS

The models used for electricity markets can be classified into several categories. Ventosa et al. (2005) identify three major categories in electricity market modelling: optimization models, equilibrium models and simulation models. Distinguishing features include the mathematical structure, market representation, computational tractability and main applications.

While in Europe the liberalization of electricity markets started in 1996, electricity market models developed beforehand had been mostly optimizing models incorporating the perspective of a single planner, i.e. the government. Through the liberalization, the integration of a market perspective in models has gained importance, which brought forth the development of alternative models such as agent-based models that are able to adequately represent the current market situation where not one central decision maker is found, but several market players pursue their individual goals. In general, agent-based models which have been developed in quite different disciplines can provide a flexible environment which allows considering inter alia learning effects, imperfect competition including strategic behaviour and asymmetric information among market participants (Tesfatsion, 2006).

Nowadays, there exists a large number of agent-based electricity market models. Depending on the research focus, the models in the literature will differ from each other with respect to various criteria.

Each agent-based model features a certain agent definition and architecture which can include several dimensions. In the first place, it is essential to define conceptually what the "agent" represents in the model. In the field of Agent-based Computational Economics (ACE) agents generally are defined as having a set of data and pre-defined behavioural rules within a computationally constructed world (Tesfatsion, 2006). Agent architecture includes the design of specific agent decision models including adaptive learning algorithms. Market modelling is another large building block of agent-based models. Given the complex nature of electricity wholesale markets and the electricity supply chain, different types of horizontally and vertically integrated markets exist. In order to analyse the existing interrelations between markets, one has to consider these markets with respect to their specific clearing rules. Depending on the spatial coverage of the model, coupling of interconnected areas might be considered as well. Similarly, agent-based models differ with regard to the time resolution as well as time scale of the simulation. The latter aspects includes, for instance, whether short-term behaviour (e.g. spot market bidding strategies) and long-term aspects (e.g. investment decisions) are jointly considered. Another important aspect of electricity market models is the representation of the electricity system's technical constraints (e.g. techno-economic aspects of generation units, grid constraints.

Three comprehensive review papers showing the large body of agent-based models for electricity markets and their distinctive features are provided by Guerci et al. (2010), Weidlich and Veit (2008), and Sensfuß et al. (2007). These literature reviews contain a comparison of the different existing models including the model presented in this paper.

Generally, having an integrated agent and market perspective, as well as a high degree of flexibility, agent-based simulation models can be used for detailed analyses of electricity markets and interactions therein. Potential applications include market power analysis or market design studies while considering the feed-in from renewable energy sources and integrated markets with respect to products, time and region.

3 POWERACE MODEL

3.1 Model Overview

The development of the PowerACE model started in 2004 and since then the model has been continuously extended and applied to various research questions.

The subject of modelling is the electricity wholesale market which is simulated for each hour of a year. Originally, the model was designed for the German market area. However, Europe's electricity markets are all liberalized and set up according to the same fundamental principles. That is why PowerACE can be used to simulate other European market areas as well. Market areas are interpreted as one "object" in the programming environment featuring different market elements, agents and input data. In order to simulate different market areas, the respective object is instantiated repeatedly.

One of the key features of the model is the integration of both short-term market developments and long-term capacity expansion planning. Thereby, interactions and feedback loops between short-term and long-term output decisions are considered. Decisions regarding the expansion of capacity, i.e. whether to install a new power plant are influenced by current and future developments in the daily electricity trading as the main source of income and vice versa.

The key modules are markets, electricity supply, electricity demand and regulatory aspects. The main players participating in the wholesale electricity market are modelled individually; small companies are represented in an aggregated form. Different types of market participants are modelled as different types of agents. Each agent takes over certain roles, makes decisions based on specified functions and either takes part in or sets rules for a respective market. A simplified overview of the model structure with two market areas is given in Figure 1.

In the following sections, the focus is set on the supply side, i.e. on generation companies which have to decide on the short-term operation of their existing power plants and on the investment in new ones.

3.2 Short-term Bidding on Electricity Markets

The short-term operation of power plants is determined by the *SupplyBidder* agent. The agent evaluates the different markets where energy or capacity of thermal power plants can be offered and determines the operation schedule and dispatch of the plants. Within PowerACE the day-ahead market is the main spot market. In accordance with the current situation in Central Western Europe, every *SupplyBidder* daily submits for each available power

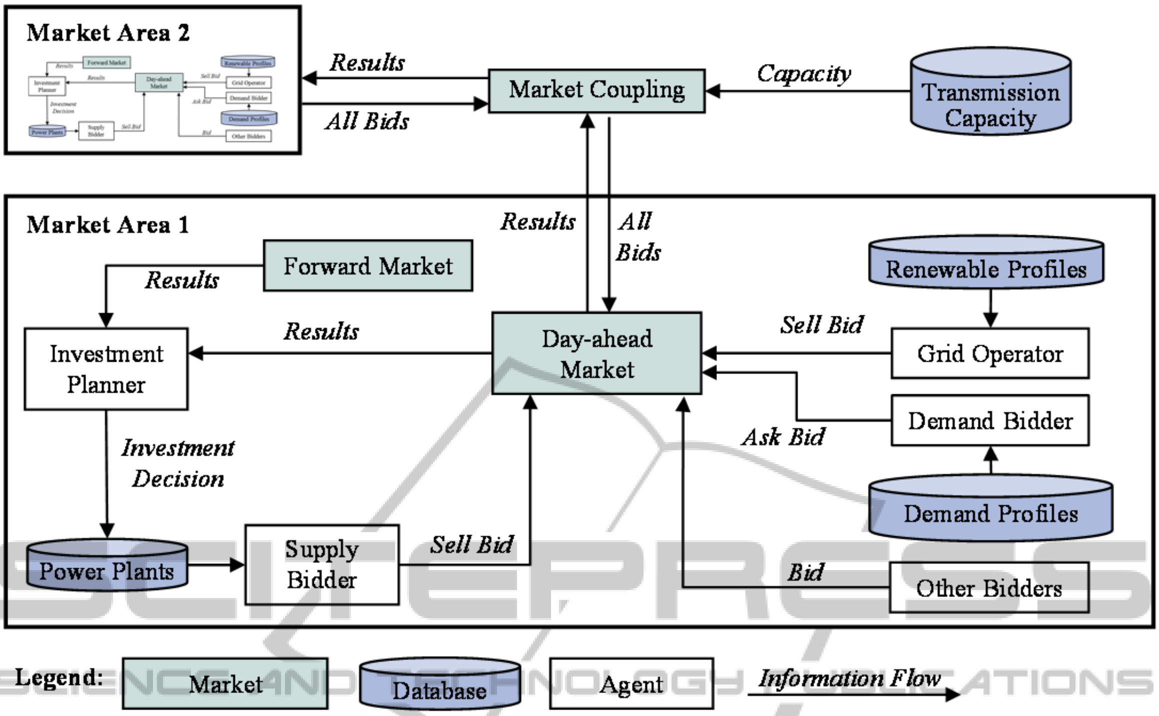

Figure 1: Simplified structure of the PowerACE model.

plant electricity supply bids to the day-ahead market. Besides for thermal power plants, also supply bids for generation from renewable energy sources, e.g. wind or biomass, are regarded. Since pumped-storage units can produce or consume electricity, they submit either buy or sell bids. The same applies to the electricity exchange with market areas which are not explicitly modelled. After receiving the bids the *DayAheadMarketAuctioneer* determines a uniform price for each hour of the next day considering all submitted supply and demand bids.

SupplyBidders are faced with an economic optimization problem, where the offered volume and price of their power plants needs to be determined and which is solved in several steps. Firstly, the available capacity $P_{i,d}$ of a power plant i on a day d needs to be determined. Power plants may not be available at all for a given day due to unexpected issues, e.g. start-up failure, or expected reasons, e.g. maintenance. Since power plants act on other markets (e.g. reserve market) as well, the reserved capacity $P_{r,i,d}$ for these markets is not available anymore for the day-ahead market bidding and needs to be subtracted from the net electrical capacity $P_{net,i}$:

$$P_{i,d}=\begin{cases} P_{net,i} - P_{r,i,d} & \text{if plant } i \text{ is available on day } d \\ 0 & \text{otherwise} \end{cases} \qquad (1)$$

Secondly, the bid price is calculated. It consists of three elements: variable costs, start-up costs and a potential mark-up. Variable costs $c_{var,i,d}$ represent the direct costs of producing one unit of electricity and are determined by the fuel price $p_{fuel,i,d}$, the power plant's net electrical efficiency η_i, the price of CO_2 emission allowances $p_{CO2,d}$, the CO_2 emission factor of the fuel EF_{fuel} and the costs for operation and maintenance $c_{O\&M,i}$:

$$c_{var,i,d}=\frac{p_{fuel,i,d}}{\eta_i}+\frac{p_{CO2,d}\cdot EF_{fuel}}{\eta_i}+c_{O\&M,i} \qquad (2)$$

Changing the mode of operation of power plants, i.e. starting up or shutting down, causes additional costs. Firstly, material is stressed mainly by temperature changes reducing life expectancy; secondly, for start-ups fuel is needed in order to reach the operating temperature of a power plant. When determining the bid price the costs from start-up and shutdown processes as an intertemporal restriction can be considered by power plant operators. In the PowerACE model, this means that for base load running power plants also lower market prices are accepted in order to avoid shutting down the power plant. In turn, start-up costs are added to the bid price for peak load power plants in order to earn start-up costs in hours where the plant is expected to be running. To estimate start-up costs a price forecast for the next day is made by an agent. The bid price $p_{i,h}$ including start-up costs in hour h is defined as follows:

$$p_{i,h}=\begin{cases}\max\left(c_{var,i,d}-\frac{c_{s,i}}{t_u}\right) & if\ \hat{p}_h < c_{var,i,d} \wedge i\in BL \\ c_{var,i,d}+\frac{c_{s,i}}{t_s} & if\ \hat{p}_h > c_{var,i,d} \wedge i\in PL \\ c_{var,i,d} & otherwise\end{cases} \quad (3)$$

$c_{s,i}$	start-up costs
t_u	number of continuous unscheduled hours per day
t_s	number of continuous scheduled hours per day
$\hat{p}_h$	predicted price for hour h
M	set of all operation-ready power plants
$BL \subset M$	set of base load power plants
$PL \subset M$	set of peak load power plants

In addition, *SupplyBidders* can increase the bid price for their power plants by a mark-up value. According to the standard economic model of perfectly competitive markets, market prices for a respective good are determined by marginal prices at all times. However, in order to cover capital expenditures and fixed costs market prices need to rise above marginal costs of supply at least in some periods. This reasoning is based on the peak-load pricing concept (Boiteux, 1964). One potential remedy is to include an additional mark-up factor in the bid price of supply capacity, which is implemented in the PowerACE model.

The value of the mark-up factor depends on the relative scarcity in the market; a higher scarcity induces a higher mark-up, which is added to the bid price:

$$p_{i,d}^{markup}=p_{i,d}+markup_h \quad (4)$$

After determining the offered volume and price for each hour of the following day the bids are submitted to the day-ahead market auctions. A comprehensive and formal description of the original short-term bidding algorithm can be found in Genoese (2010).

3.3 Coupling of Interconnected Markets

European electricity markets are interconnected via high-voltage transmission lines. Since electricity flows according to physical laws and interconnector capacities are limited, these capacities have to be allocated to market participants otherwise transmission lines might get congested. Management methods are required to avoid congestion and to efficiently use cross-border transmission capacities.

Since 2010, a market coupling approach has been implemented in Central Western Europe which complies with the European Union’s general principles of congestion management (e.g. non-discriminatory, market-based). Market coupling describes the implicit auctioning of interconnection capacity through power exchanges for predefined zones (market or bidding areas). The market coupling operator clears the energy markets of the participating market areas simultaneously and determines implicitly the commercial flows between markets areas as well as the prices. The market coupling approach maximizes the social welfare by optimizing the selection of bids while considering limited transmission capacity. The transmission capacity is determined up-front based on defined rules (EPEX Spot, 2010).

In accordance with the CWE Market Coupling architecture, market coupling is implemented within PowerACE for the day-ahead market and market participants submit their bid curves to the local power exchanges based on the described method in section 3.2.

In PowerACE the *MarketCouplingOperator* takes over all processes related to the market coupling. For that purpose, the operator receives all day-ahead bids from the local power exchanges. Market coupling itself can be formulated as an optimization problem with the objective to maximize social welfare. Since PowerACE currently only considers hourly bids with a fixed price, the original COSMOS algorithm used for the CWE Market Coupling (APX-ENDEX et al., 2010) can be simplified and the mathematical problem is formulated as follows (e.g. Meeus et al., 2009):

$$\max_q \sum_b \left(\sum_d P_{b,d}Q_{b,d}q_{b,d} - \sum_s P_{b,s}Q_{b,s}q_{b,s}\right) \quad (5)$$

subject to

$$q_{b,d}\,,\ q_{b,s} \leq 1 \quad (6)$$

$$\sum_d P_{b,d}Q_{b,d}q_{b,d} - \sum_s P_{b,s}Q_{b,s}q_{b,s} + \sum_{b(to)} Cap_{b,b_{(to)}} - \sum_{b(from)} Cap_{b_{(from)},b} = 0 \quad (7)$$

$$Cap_{b(from),b(to)} \leq Cap_{b(from),b(to)}^{max} \quad (8)$$

where the indices d and s indicate demand and supply variables, respectively. b denotes the market (bidding) area, P_i the bid prices and Q_i the bid volumes. $q_{b,d}$ and $q_{b,s}$ are the acceptance rates of the corresponding demand and supply bids. $Cap_{b(from),b(to)}$ equals the determined capacity between two market areas. $Cap^{max}_{b(from),b(to)}$ denotes the upper limit for the transmission capacity between to market areas and is given exogenously based on current values from the European Network of Transmission System Operators for Electricity (ENTSO-E).

The constraints ensure that supply and buy bids do not exceed their maximum volume (6), that supply and demand including exports as well as imports in market areas are balanced (7) and that the limitation on the transmission capacity (8) is not violated. In this form, the problem is linear and can be solved with common solvers.

Optimization results are the acceptance rates for each submitted bid and the commercial utilization of transmission capacity. Furthermore, the algorithm determines the market prices of electricity one day-ahead of delivery in the coupled bidding areas and the implicit prices for transmission capacities, which are only different from zero if lines are congested. Prices are sent to the local market areas and processed by the supply agents.

3.4 Long-term Investment Planning

In the model generation companies can also make decisions regarding their long-term capacity extension through investments in new power plants. The responsible agent is called *InvestmentPlanner*.

The basic methodology is based on a discounted-cash flow valuation of predefined technology options. For that purpose the *InvestmentPlanner* makes a forecast of the expected hourly electricity prices during the investment period and calculates the expected yearly gross profit. After accounting for fixed costs and capital expenditures, the net present value is calculated. A formal description is provided in Genoese (2010).

The quantity of the installed capacity is based on the expected development of market shares within the following five years taking future demand and electricity generation from renewable energy sources into account. As long as the net present value of the investment options is positive and there is need for new capacity, new power plants are built by the *InvestmentPlanner*. After the construction phase, whose length depends on the technology option, the new power plants can generate electricity that can then be sold in the markets.

3.5 Input Data and Technical Implementation

For the considered market areas each thermal power plant with a capacity of at least 10 Megawatt is stored together with its main relevant techno-economic characteristics (e.g. net electrical efficiency, variable and fixed costs, yearly availability) in the database of the model.

The model database includes investment options for different power plant technologies with its relevant characteristics and the electricity feed-in from renewable energy sources. The electricity demand is represented by the aggregated consumption of all consumers connected to the public power supply.

For market coupling, transmission capacities between interconnected market areas are required. Since not all neighbouring countries are always part of a simulation, the electricity exchange with these countries is based on historical values. Prices for fuel and CO_2 emission allowances are required for the calculation of the variable generation costs. Most time series data is stored with hourly values, but sometimes only less detailed values, e.g. for lignite prices, are available.

The model's results include the hourly spot market prices in the simulated wholesale markets, the investments in new capacity and the commercial flows between interconnected market areas. Since the model considers the wholesale day-head market as the only trading place for electricity, bilateral day-ahead contracts are not part of model's results.

PowerACE is implemented in the object–oriented programming language Java and can simulate each hour of recent historical years as well as future years up to 2050. The simulation runs are comparatively quick in terms of computing time. Yearly runs for one market area last only a few minutes, which is a small fraction of the several hours that optimization models with a similar amount of details may take.

4 EXEMPLARY APPLICATIONS

The PowerACE model has been used for various research analyses in the past. For instance, Sensfuß et al. (2008) find a considerable impact of the subsidised renewable electricity generation in the short run on spot market prices in Germany. The impact of emissions trading on electricity prices is explored by Genoese et al. (2007). The authors find for the years under consideration that a large part but not the totality of the CO_2 emission allowance price is added by the generation companies to the variable costs during the bidding process. A thorough analysis of the model's capacity to adequately reproduce the main characteristics of the German electricity market can be found, for example, in Genoese (2010).

In the following sections, additional recent analyses are presented.

4.1 Market Coupling between Germany and France

Based on the algorithm described in section 3.3, effects from a market coupling between the German and French day-ahead electricity markets are analysed. Both markets represent the two largest in Europe in terms of electricity consumption and are part of the CWE Market Coupling. To the authors' best knowledge this is the first agent-based approach that includes the coupling of different market areas based on the current market situation.

The simulation of the model coupling is performed for the year 2012. In the *Single Markets* scenario, there is no coupling of the two markets, i.e. no exchange between Germany and France is considered. The *Model Coupling* scenario uses the optimization routine for the coupling of the German and French market areas. The electricity exchange with other countries (e.g. between France and Spain, Germany and Poland) is in both scenarios given exogenously based on historical data.

The *Model Coupling* scenario shows lower average prices than the *Single Market* scenario, while the price decrease is stronger in France than in Germany. The more pronounced effect for France can be explained, to some extent, by the supply curves' shapes of the two market areas. The French supply curve has only a gentle slope for a large part of the country's capacity because of the low variable operating costs of nuclear power stations. However, the small part of the remaining capacity consists of notably more expensive fossil fuel-fired units. These units are often called upon in the *Single Markets* scenario. When coupling the markets, the expensive units in France are less frequently used because cheaper electricity can be imported from Germany.

The change in market prices does not imply that all market participants, buyers and sellers, benefit. The results in this simulation indicate that mainly the consumers benefit from the market coupling which is consistent with expectations given a lower average price. The social welfare (sum of consumer surplus, producer surplus and congestion revenue) increases with market coupling, which could be expected, as the clearing algorithm tries to maximize this value.

In the *Model Coupling* scenario the available transfer capacity is fully used in 65% of the cases. The high usage of the full capacities and the price effect of the coupling can be seen for a period of 100 hours in figure 2. Expanding (e.g. doubling) the capacity amplifies the price reduction in both countries; while the additional effect is smaller in France than in Germany, the total price reduction is still stronger in France. In case of sufficient capacity there are identical prices in all hours, which is equal to the situation of having one completely integrated market.

Regarding only market coupling between two countries, in this case Germany and France, while the exchange with other country is based on historical values, is, of course, a simplification. Germany, for instance, has interconnections with nine countries while France is connected to seven countries. Amongst those countries are some that take part in the market coupling as well, e.g., Austria, Belgium or the Netherlands. Hence, the effects from the market coupling between Germany and France in this paper might be overstated, since either country would exchange electricity with other countries, if this as well is no longer static and less costly than the exchange with Germany or France, respectively.

The presented results also depend on information which is not publicly available and therefore needs to be estimated, such as the operation and maintenance costs of power plants. Deviations between estimated and real world values could, of course, alter the results of the simulation.

4.2 PowerACE LAB

Besides the computational model, there exists a laboratory version, "PowerACE LAB", where real-life participants can assume the tasks of software agents. Thus, the core agent-based simulation model is supplemented by elements from experimental economics and role-playing games (Genoese and Fichtner, 2012).

In literature, two approaches are distinguished in combining agent-based models and role playing games. Barreteau (2001) proposes a parallel existence of agent-based models and role playing games. Hence, the model is rebuilt in a simplified

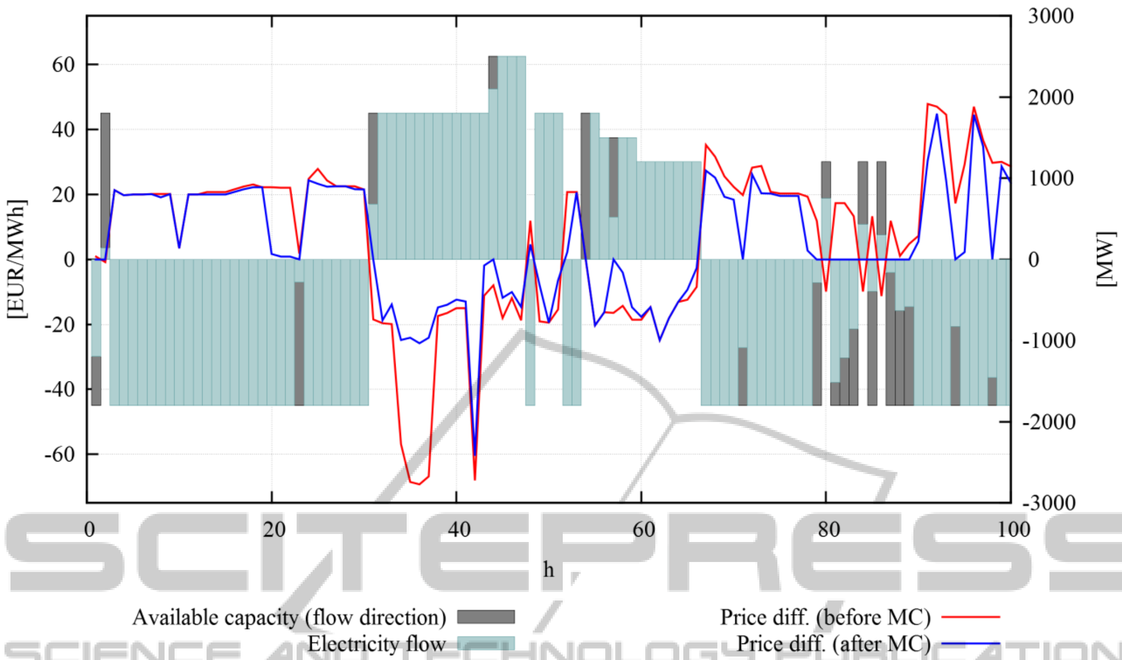

Figure 2: Simulated electricity flow and price difference (before and after market coupling) between Germany and France for a period of 100 hours in 2012.

version as a game. The main goal of this approach is to increase the acceptance of the model. Guyot and Honiden (2006) develop an agent-based participatory approach, where real participants are integrated into the model by (partly) controlling the agents' actions. For this, user interfaces have to be developed. In the PowerACE Lab version, the agent based participatory approach is used.

Currently, in PowerACE Lab two modules exist where human participants can interact. The participants either simulate the power trading or the investments in new generation capacity. In the trading module, the participants receive the same information as the computer agents. Each participant has a list of daily available power plants with all the relevant technical and economic data, e.g. installed capacity, fuel costs and efficiency. In addition, a forecast of the day-ahead prices is presented. Based on this information, the participants submit their bids. When all players have successfully completed their task, the market clearing price is computed analogously to the computational model. The players have the possibility to adopt their strategies in each round in order to maximize profits.

In the investment module, the players can carry out investments according to the power and fuel price forecast and by taking into account the decreasing capacities due to the limited technical lifetime of existing power plants.

The players' decisions and chosen strategies can be used to improve the behaviour of the computer agents. Computer agents and real participants can coexist as well in the simulations.

5 CONCLUSIONS AND OUTLOOK

Agent-based simulation in general and the PowerACE model in particular are useful means to analyse different aspects of electricity markets. The market and agent perspective as well as the flexibility of agent-based simulation models allows us to thoroughly analyse electricity markets and interactions therein. The PowerACE model is a detailed bottom-up simulation model which integrates short-term market operations and long-term capacity planning while the most important market participants are represented by different agents. The model has been successfully used for various analyses in the context of electricity markets.

Given the continuously changing economic and regulatory environment in the power sector, several enhancements to the model are currently in progress.

In order to reflect the European market integration, the model scope is extended to several market areas which can be simultaneously run and coupled. Model coupling clears the energy and capacity markets simultaneously and determines an optimal solution to the plant dispatch in the interconnected market areas considering limited commercial transfer capacities. The model coupling routine presented in this paper offers a socially beneficial opportunity to interconnect electricity markets compared to a situation where no market coupling occurs. The results for Germany and France show that the average market price is lower in both countries, while the price decrease is stronger in France than in Germany.

The methodological approach of PowerACE has nonetheless some limitations. Regarding the supply of electricity, additional technical constraints concerning the operation of power plants (e.g. minimum downtimes or partial efficiency levels) could further improve the model. Furthermore, the perspective is limited to the supply of electricity, which differs from the real world situation where also the heat demand influences the usage of combined heat and power plants.

Given the flexible modelling framework future model extensions could include the development of a generally scalable model version in order to simulate micro-systems as well as larger systems (e.g. Europe) with additional market elements (e.g. intraday market). Concerning the decision making process of agents, the refinement of the investment module and the integration of different aspects of uncertainty is another possibility to extend the model. Regarding the design of electricity markets, the remuneration of power plants by capacity mechanisms in order to ensure system reliability is another topic of research that is currently explored within the model.

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REFERENCES

APX-ENDEX; Belpex; EPEX Spot (2010): COSMOS description - CWE Market Coupling algorithm. Retrieved from http://static.epexspot.com/document/20015.

Barreteau, O.; Bousquet, F.; Attonaty, J. (2001): Role-Playing Games for Opening the Black Box of Multi-Agent Systems: Method and Lessons of Its Application to Senegal River Valley Irrigated Systems, *In: Journal of Artificial Societies and Social Simulation 4 (2)*.

Boiteux, M. (1964): Marginal Cost Pricing in Practice. London: Prentice-Hall.

EPEX Spot (ed.) (2010): Project Document – A report for the regulators of the Central West European (CWE) region on the final design of the market coupling solution in the region, by the CWE MC Project. Retrieved from http://static.epexspot.com/document/7616/01_CWE_ATC_MC_project_documentation.pdf.

Genoese, M. (2010): Energiewirtschaftliche Analysen des deutschen Strommarkts mit agentenbasierter Simulation. Baden-Baden: Nomos.

Genoese, M.; Fichtner W. (2012): PowerACE LAB: Planspiel Energiewirtschaft. In: WiSt 41 (6), pp. 335-339.

Genoese, M.; Sensfuß, F.; Möst, D.; Rentz, O. (2007): Agent-Based Analysis of the impact of CO_2 Emission Trading on Spot Market Prices for Electricity in Germany. *In: Pacific Journal of Optimization 3 (3)*; pp. 401-424.

Guerci, E.; Rastegar, M. A.; Cincotti, S. (2010): Agent-based Modeling and Simulation of Competitive Wholesale Electricity Markets. *In: Handbook of Power Systems II. Berlin*, Springer, pp. 241–286.

Guyot, P.; Honiden, S. (2006): Agent-based Participatory Simulations: Merging Multi-Agent Systems and Role-Playing Games. *In: Journal of Artificial Societies and Social Simulation 9 (4)*.

Meeus, L.; Vandezande, L.; Cole, S.; Belmans, R. (2009): Market Coupling and the importance of price coordination between power exchanges. In: *Energy Economics 34 (3)*, pp. 228–234.

Sensfuß, F. (2007): Assessment of the impact of renewable electricity generation on the German electricity sector: An agent-based simulation approach. Retrieved from http://digbib.ubka.uni-karlsruhe.de/volltexte/documents/188330.

Sensfuß, F.; Genoese, M.; Ragwitz, M.; Möst, D. (2007): Agent-based Simulation of Electricity Markets - A Literature Review. In: Energy Studies Review 15 (2).

Sensfuß, F.; Ragwitz, M.; Genoese, M. (2008): The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. In: Energy Policy 36 (8), pp. 3086–3094.

Tesfatsion, L. (2006): Agent-Based Computational Economics: A Constructive Approach to Economic Theory. In: Judd, K. J.; Tesfatsion, L. (eds.). *Handbook of Computational Economics*, Volume 2.

Agent-Based Computational Economics. North-Holland.
Ventosa, M.; Baíllo, Á.; Ramos, A.; Rivier, M. (2005): Electricity market modeling trends. In: *Energy Policy 33 (7)*, pp. 897–913.
Weidlich, A.; Veit, D. (2008): A critical survey of agent-based wholesale electricity market models. In: *Energy Economics 30 (4)*, S. 1728–1759.