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Agent-based simulation of electricity markets – A literature review

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Abstract

Liberalisation, climate policy and promotion of renewable energy are challenges to players of the electricity sector in many countries. Policy makers have to consider issues like market power, bounded rationality of players and the appearance of fluctuating energy sources in order to provide adequate legislation. Furthermore the interactions between markets and environmental policy instruments become an issue of increasing importance. A promising approach for the scientific analysis of these developments is the field of agent-based simulation. The goal of this article is to provide an overview of the current work applying this methodology to the analysis of electricity markets.

Contents

1 Introduction

The electricity sector in Europe and the USA is undergoing considerable changes. The liberalisation of electricity markets, climate policy and the promotion of renewable energy change the framework conditions of this formerly strictly regulated field. In the United States the outages of electricity supply in California in 2001 and the blackout on August 14, 2003 leaving 50 million people without electricity (U.S.-Canada Power System Outage Task Force, 2004) have changed the way electricity markets are regarded. Based on these circumstances new questions arise: How can liberalised markets be developed without endangering the security of supply? How can the efficiency of market mechanisms be ensured in an environment with only few players? Which policies are adequate to ensure environmental goals like climate protection and promotion of renewable energy under market conditions? In order to deal with these issues new scientific tools for the analysis of developments in the electricity sector have to be developed. A promising approach is the development of agent-based simulations.

Before entering into a discussion of the different modelling approaches of the electricity sector it may be valuable to describe some of the major characteristics of electricity markets. One central aspect of electricity is that is difficult to store in large quantities. Another important aspect is that the stable operation of the electricity grid requires that electricity demand and supply are always in balance. This situation requires that there is always enough generation capacity to satisfy demand. Therefore it is common that the grid operators who are responsible for the stability of the grid purchase balancing capacity in order to be able to balance the grid in case of unforeseen developments such as plant outages. If the gap between electricity demand and supply exceeds the available balancing capacity the entire electricity system can break down. Therefore it is important to ensure that the electricity system creates enough generation and grid capacity in order to ensure the stability of the system in the long run. In the given context it is also important to note that the infrastructure of the electricity sector consisting of the electricity grid and the generation capacity requires large investments. This leads to the situation that electricity markets are in many cases dominated by a limited number of players. As consequence the policy makers or regulators face the problem that the electricity system has to create enough incentives to build and maintain the infrastructure in terms of generation capacity and transmission capacity without creating exaggerated profits for the oligopoly of players owning the generation capacity.

In general three major bottom-up approaches to model electricity markets can be distinguished: optimisation models, equilibrium models and simulation models (Ventosa et al., 2005). In most cases agent-based simulations can be classified as simulation models although some agent-based models try to integrate routines from other approaches such as optimisation models for the optimal utilisation of a power plant portfolio (see Scheidt, 2002). In addition Computable general equilibrium [CGE] models or other macroeconomic modelling approaches are mainly used for the top-down analyis of macroeconomic developments of the sector. In most cases they apply a high level of aggregation which lacks the detail level necessary to analyse short term developments on electricity markets which are heavily influenced by technical detail and player interactions. A common application of optimisation models in the electricity sector is the capacity expansion planning of public utilities. Despite their capability to integrate a high level of detail these models lack the capability to integrate player interactions, especially if the players deviate from the principle of pure financial profit maximization. A central strength of the agent-based simulation models is the possibility to deviate from "normative" equilibrium conditions or strategies. As an example the modelling approaches stated above are not suitable to analyse the development of electricity prices for households in a liberalized electricity market because households apply a different rationale (Bakay and Schwaiger 2004; Price 2003).

Based on these considerations agent-based simulation models have experienced an increasing popularity amongst electricity market modellers. This development can be explained by the additional opportunities that this modelling paradigm offers for the analysis of economic systems, as compared to more traditional equilibrium models or optimisation models. Aspects like learning effects in repeated interactions, asymmetric information, imperfect competition, or strategic interaction and collusion can be included in a more realistic way in agent-based models. Also, the interaction structure and the agents' individual behaviour can be specified more freely as compared to optimisation and equilibrium models. Increasingly powerful computational resources as well as the development of toolkits[1] that facilitate the implementation of agent-based models in object-oriented programming languages have further pushed applications of

1 For a comparison of different agent toolkits, the reader is referred to a detailed evaluation of four Java libraries for agent-based simulation in the social sciences, prepared by Tobias and Hofmann (2004). Other helpful pointers are given in a paper by Gilbert and Bankes 2002 and in a review of software products by Mangina 2002.

agent-based simulation. The concept of agent-based simulation has the potential to become a valuable modelling approach in addition to existing tools that are already used for the analysis of the electricity sector. However, the concept is very demanding in its data requirements and empirical validation is a crucial issue to be dealt with in order to reach a high level realism.

The fact that one of the central advantages of agent-based simulation is its flexibility is also reflected in the diversity of definitions. While there are some commonly quoted definitions of the term “agent” in the field of software engineering (Wooldridge and Jennings, 1995; Wooldridge, 2002; Franklin and Grasser 1997) a review of existing agent-based simulation models by Drogoul et al. (Drogoul, et al., 2002) shows that those simulations use a “weak” notion of agents at the metaphorical or conceptual level. In these cases agents constitute a convenient model for representing autonomous entities without being themselves autonomous in the resulting implementation of these models (Drogoul, Vanbergue and Meurisse, 2002). The same is true for the research field of Agent-based Computational Economics, where the term “agent” broadly refers to bundled data and behavioural methods representing an entity that constitutes a part of a computationally constructed world (Tesfatsion 2006). As examples of possible agents Tesfatsion mentions individuals, social groupings, institutions, or biological and physical entities. Thus, she states, agents can range from active data-gathering decision-makers with sophisticated learning capabilities to passive world features with no cognitive functioning.

The aim of this paper is to provide an overview of the recent work in the field of agent-based simulation of electricity markets. Due to the dynamic development of this research area the presented review can not ensure completeness. However, care has been taken to include the most relevant works that are known to the authors. Since the field of agent-based simulation of electricity markets is new the review is extended beyond the literature that is available in Journals in order provide an adequate picture of recent research. The presented review should provide a helpful guidance through the literature with pointers to ongoing projects[2], especially to newcomers in agent-based electricity market modelling. In order provide a structure for the literature survey the reviewed papers are grouped into three main categories of ongoing research: 1. Analysis of market

2 A very good resource on the latest projects and papers in agent-based electricity market modeling is also a web site maintained and regularly updated by Leigh Tesfatsion: http://www.econ.iastate.edu/tesfatsi/aelect.htm

power & design, 2. Modelling agent decisions 3. Coupling of long-term and short-term decisions. The paper is structured accordingly. Within these main categories some major subcategories have been identified. In the case of market analysis the number and actual features of implemented markets plays a major role starting from a single market up to multiple markets or the integration of markets for other commodities such as gas. Other subcategories are the integration of players and transmission constraints. The actual concept or implementation varies within the literature. However, there is a common tendency towards increasing complexity of the described models. An overview of the features that can be identified in the reviewed literature is given in Figure 1.

However, it has to be pointed out that there is some overlap between these categories (see also Figure 2 with selected examples). Some parts of the reviewed papers may have contributed to more than one of these categories, or to additional research questions. In these cases the papers have been classified according to best knowledge of the authors. Another aspect considered in the classification of single papers is the goal to show the contributions of a given research group within one section wherever possible in order to enable the reader to get an impression of the model development trends over time. The final section of the paper contains a summary and some concluding remarks.

Figure 1: Overview of main categories and different contributions of ongoing research

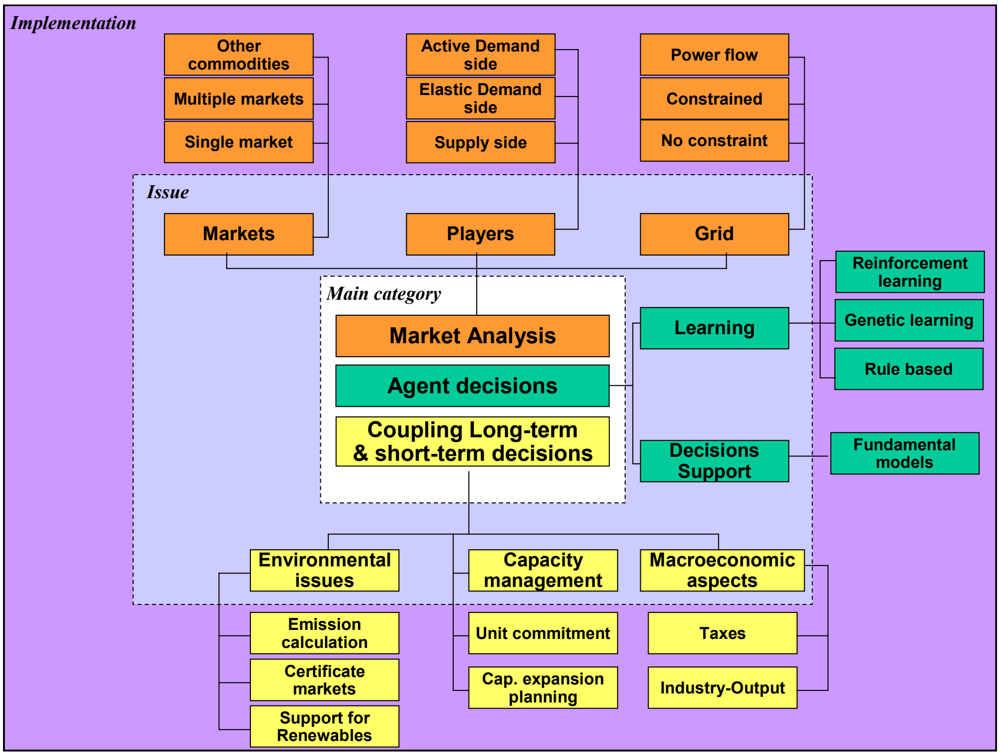
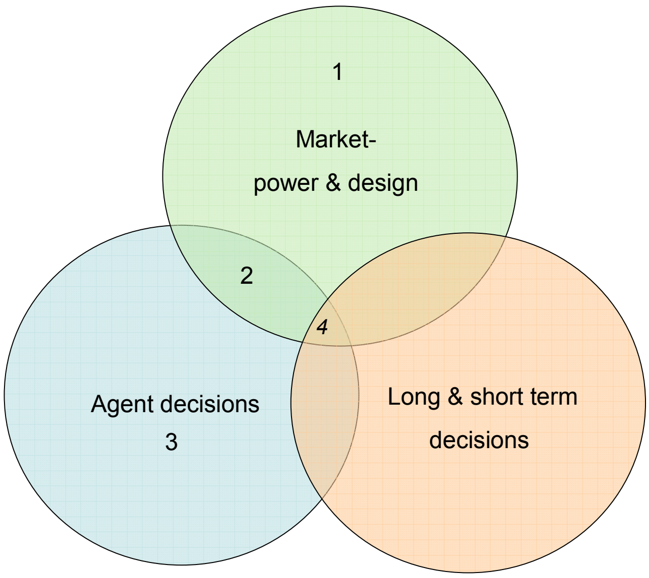


Figure 2: Overview of the main research categories in the reviewed literature



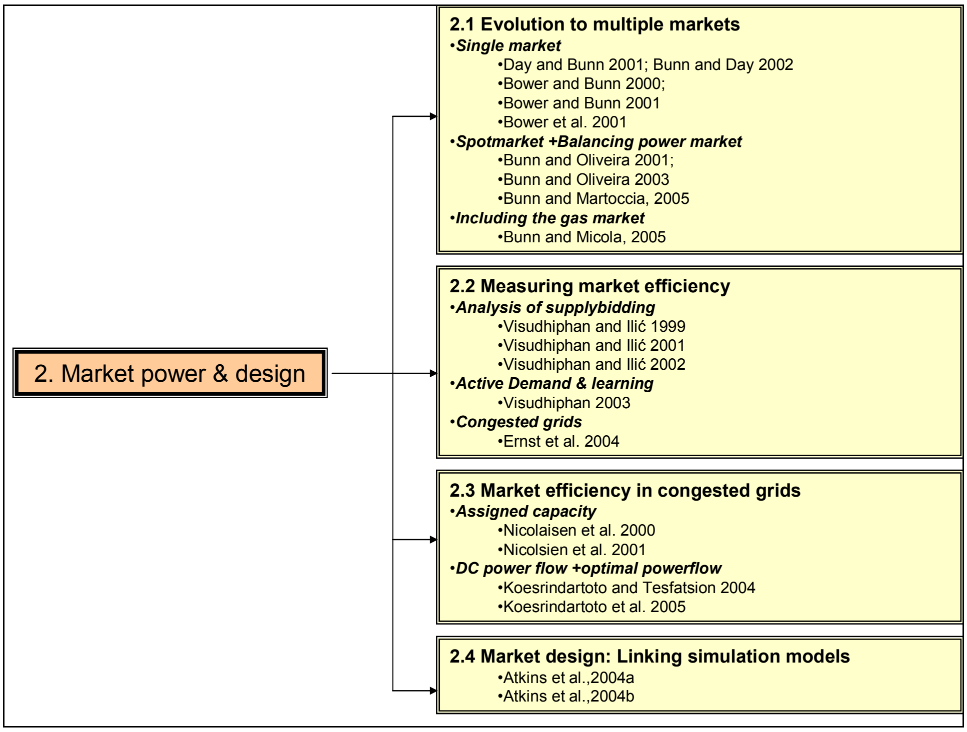
1.	Chapter 2.1	e.g. (Bower and Bunn,2000)
2.	Chapter 3.1	e.g. (Koesrindartoto, 2002)
3.	Chapter 3.2	e.g. (Visudhiphan 2003)
4.	Chapter 4.1	e.g. (Conzelmann et al. 2004);

Source: (own visualisation)

2 Models to analyse market power and market design

The current work focussing on market design is mainly triggered by the restructuring of electricity markets in the USA and Europe. This section introduces the work carried out at London Business School, Iowa State University, Los Alamos National Laboratory and a series of papers by Ilic and Visudhiphan as remarkable examples of the ongoing research. An overview of the main categories and the analysed papers is given in Figure 3.

Figure 3: Overview of reviewed papers on market power and design



Source: (own visualisation)

2.1 Analysis of the market power of utilities: Evolution to multi-market models

One of the pioneers in the field of agent-based simulation of the electricity sector is a research team at London Business School. Day and Bunn (Day and Bunn, 2001) describe a simulation where generation companies bid their individual piece-wise linear supply function in a market with uniform price market clearing. The generation companies are modelled as daily profit maximisers who assume that the competitors bid the same supply function as they did in the previous day. In addition to the profits obtained from electricity sales, companies can also earn revenue from so-called contracts for differences, i.e. financial hedging contracts that they engage in with buyers of electricity. Each company selects its best action through an iterative optimization routine that calculates the supply function that the company bids into the pool market with respect to mentioned conjecture about the opponent's actions and a given volume of contracts for differences. Electricity demand is represented by an aggregate demand function with a defined slope. Day and Bunn evaluate their model by comparing the supply functions obtained from the computational model with the equilibrium in continuous supply functions that would be obtained through the approach formulated by Klemperer and Meyer (1989). A central finding is that the results are reassuringly close in the studied scenario, which models competition between the three largest fossil fuel generating companies in the England and Wales pool. They conclude that the computational approach can also deliver realistic results for more complex scenarios that cannot be represented in the analytical supply function equilibrium model. The computational model is then applied to analyse different options for the second round of plant divestiture in England and Wales in 1999. In the simulation runs the demand slope and the volume of contracts for differences are varied. Their results show that the analysed divestment options result in lower average percentage bids above marginal cost. But, the authors conclude, the proposed divestiture still leaves market power with generators in the short term, and could result in prices more than 20% above short-run marginal costs.

In a later paper the authors (Bunn and Day, 2002) present this model as a competitive benchmark against which to assess generator conduct and to diagnose the separate causes of market structure and market conduct in situations where prices appear to be above marginal costs. For the tested scenarios the simulated system supply functions are above the marginal cost function and significantly below the system supply curve observed in the England and Wales pool on an exemplary day, except at low demand levels. This leads the authors to the conclusion that the extent to which the simulated supply functions are above the marginal cost function is caused by the market structure. Based on the fact that the observed system supply functions in the real-world market are still above the simulated system supply functions Bunn and Day conclude that there is collusion within the market, thus identifying a problem of market conduct.

Bower and Bunn present an agent-based simulation of the England and Wales electricity market in the year 2000 (Bower and Bunn, 2000). The simulation is designed to compare different market mechanisms. Examples are the comparison of daily bids versus hourly bids and the comparison of uniform price and discriminatory settlement. In the given simulation, generation agents bid on a single electricity market. The electricity demand is modelled by a price inelastic aggregate demand curve. Agents are endowed with a simple reinforcement learning algorithm which is driven by the goal to maximise profits and to reach a given utilisation rate of a power plant. The agents can choose between four strategies, e.g. lowering prices when the expected utilisation is not met. Since bids are calculated for every plant, generation companies with more plants get more insights into the market. The memory of the agents is limited to two days. A more detailed discussion of the results of an application of this model can be found in (Bower and Bunn, 2001). The results of the agent-based simulation show that the discriminatory settlement leads to higher prices than uniform price settlement. Another finding is that a shift to hourly bidding leads to higher prices which can be explained by the fact that the inelastic demand helps the generation companies to reach high market prices in peak demand periods. In a next step the simulation results are compared to classical economic models of monopoly, duopoly and perfect competition supporting the simulation outcomes with regard to the comparison of uniform and discriminatory settlement.

In (Bower et al., 2001) an application of the developed model for the simulation of the German electricity sector is described. Thereby the German market is simulated as a day-ahead bilateral market with simultaneous bidding and pay as bid market clearing. The demand is represented by an aggregate demand curve. Transmission constraints or costs are neglected. In the given case study the impact of the mergers between RWE/VEW and Preussen Elektra/Bayernwerk creating Germany's biggest electricity utilities is analysed in different simulation settings including plant closures and lower utilisation targets for power plants. In these scenarios electricity prices rise considerably as an effect of the mergers.

An extension of the agent-based simulation is described by Bunn and Oliveira (Bunn and Oliveira, 2001). The given paper explicitly models electricity demand as actively bidding supplier agents. Supply-agents are characterized by a given market share, contract cover, a given retail price, the mean prediction error in forecasting the contracted load and a search propensity which indicates the agents willingness to search for new strategies. The supplier agents are driven by the goal to maximize daily profits while keeping balancing market exposure caused by insufficient contract cover close to a target value. Another enhancement of the model is a more detailed simulation of the supply-side by integrating plant cycles and availability into the generator characteristics. Other aspects like contract cover, search propensity and goals are similar to the supply agents. The extended model incorporates the balancing power market as an additional market. Both markets are modelled as sequential markets. Trading takes place on a day-ahead basis for single hours. The balancing power market is executed after the power exchange generators and suppliers are allowed to bid on the balancing markets in order to correct load prediction or missing contract cover.

In a case study Bunn and Oliveira (Bunn and Oliveira, 2003) use the developed model in order to analyse whether two generation companies on the UK electricity market are capable of increasing their profits by manipulating market prices. They can show that in a one shot Betrand game generators are capable of reaching prices above marginal cost. Unilateral capacity withholding leads to increased profits. Based on these results Bunn and Oliveira argue that profit margins are not a good indicator to evaluate market power abuse and they state that learning in repeated games has to be taken into account. In order to reach more realistic results the developed agent-based simulation is applied for an analysis of the England and Wales electricity market in the year 2000. The simulation is carried out for six typical demand profiles and six predefined strategies for the two generators. Results of the simulation runs indicate that only one generator is capable of increasing power exchange prices unilaterally. In order to manipulate prices profitably both generation companies have to act together. However, prices on the balancing market seem to be more robust against manipulation from both players. Based on these results the authors argue that additional insights can be gained in repeated games using agent learning algorithms to explore phenomena like implicit collusion.

Recently the described model has been applied to the analysis of market power on the electricity market in England and Wales (Bunn and Martoccia, 2005). A new direction of research seeks to extend the developed simulation platform for the analysis of the impact of crossholdings and vertical integration. Thereby the analysis of the gas to power value chain is within the centre of research. A new challenge is the simulation of two markets for different commodities (Micola et al., 2006).

2.2 Using agent-based simulation to measure market efficiency

Another group contributing to the field of agent-based simulation of electricity markets is a group led by Marija Ilić. In (Visudhiphan and Ilić, 1999) a first agent-based simulation of electricity markets is presented. It simulates a spot market with uniform-price market clearing. Electricity demand is modelled by a price-elastic demand curve. The supply side is represented by generator agents bidding on the spot market based on information on their marginal cost and the available capacity. Generators can either pursue a profit maximization strategy or enter a competition to be a baseload generator.

Bids can either be submitted as a linear supply function or a single step supply function for one day. In case studies the model is tested with three generators on a day-ahead market and an hour-ahead market. The resulting prices in the hour-ahead market tend to be lower than in the day-ahead market. In general the elasticity of electricity demand has considerable impact on the ability of generators to exercise market power.

In their second paper on an agent-based spot market model Visudhiphan and Ilić (Visudhiphan and Ilić 2001) report on simulation results from a model in which adaptive agents can show strategic behaviour and learn to improve their bids. The research question is the analysis of market power in an electricity spot market. In the described model the agents' decision process is composed of the bidding quantity determination and the subsequent bidding price determination. Agents strategically withhold capacity when their expected profit after withholding is higher than without withholding. As for the bid price setting decision several strategies are proposed and each agent is assigned one strategy at the beginning of the simulation.

Agents have complete knowledge of the forecasted total load and of the system marginal cost function. Each agent records data about the market outcome in previous market rounds. The outcomes are each mapped to predefined discrete load ranges, so that each agent's memory can be represented as a matrix with rows corresponding to the different load ranges and columns corresponding to the market rounds. Agents also distinguish whether the resulting market price in one round is a result of strategic or competitive behaviour, and store this information likewise. On the basis of the stored market data six strategies for setting the marginal-unit bidding price for the next round are defined.

Simulation results are presented for two scenarios of available capacity. For each of the capacity scenarios, strategic and competitive (i.e. marginal-cost) prices are compared. Visudhiphan and Ilić come to the conclusion that generators are able to raise market prices if they bid strategically. This is observed not only for hours of high electricity demand but also for low-demand hours. However, a distinction between the success of different price or quantity bidding strategies is not made in the presented paper.

In a later paper the same authors (Visudhiphan and Ilić 2002) describe an enhanced electricity market model in the form of a dynamic bidding game. This model comprises different time scales, i.e. short-term (bidding strategies), medium-term (maintenance scheduling), and long-term (new entry, shut-down and merger) horizons. In order to make the model manageable, the three levels of short, medium and long-term decisions by the agents are assumed to be fully separable and are formally described as maximisation problems. In the same way as in the previous paper the short-term bidding strategy is split into the quantity determination and a subsequent price determination.

As an ultimate aim of their work, the authors of the presented paper state a meaningful quantifiable market efficiency measure, which accounts for the electricity-related complexities, the available information, and the particularities of market structures. The agent-based approach is supposed to help to distinguish situations in which market power has been exerted from situations where effects of technical constraints might have raised market prices. The decision problems formulated in the presented paper are one element in this work in progress; simulation results are not reported in the paper.

In Visudhiphan 2003 an agent-based simulation platform is presented where power-producing agents with non-uniform portfolios and load serving entities engage in an electricity market with uniform clearing or discriminatory clearing. Several learning algorithms are tested with different parameters to show the impact on the simulated price dynamics. An own learning algorithm is introduced which incorporates a capacity withholding strategy and a memory for past market developments. The analysis shows that learning algorithms have a considerable impact on the result. The validation of the agent-based simulation with real market data is discussed but Visudhiphan points out that most of the data necessary to replicate real world conditions such as plant outages are confidential and draws the conclusion that a numerical validation is not possible in the given case. The agent-based simulation is applied to compare the impact of uniform and discriminatory pricing markets on market results with different learning algorithms. The result is heavily influenced by the learning algorithm but the discriminatory pricing tends to have a higher market price which is in compliance with the results obtained by Bower and Bunn (2001). In another application of the model the impact of an active load serving entity representing electricity demand is analysed. The results show that active demand bidding with price elastic electricity demand can limit the capability of power generators to raise prices.

Another agent-based simulation integrating grid constraints is presented by Ernst et al. (Ernst et al., 2004). In the given simulation electricity demand is integrated by a load agent with inelastic electricity demand. Generators and load agents are connected to a two node power system. Market clearing is implemented as a linear programming problem with the goal to satisfy electricity demand at the lowest cost. Grid constraints can lead to higher prices in congested regions of the grid. In a case study the simulation is applied to analyse the impact of congestion and additional generation capacity. Therefore simulations are run with two and three generators respectively, with and without grid constraints and with grid congestion. In another simulation the impact of aggregating several generators to a generation portfolio is analysed. The results show that this aggregation increases the generators' capability to exercise market power. But the simulation runs with grid constraints show that congestion can change the market power of single agents or even a generation portfolio considerably.

2.3 Analysis of market efficiency in congested electricity grids

The research at Iowa State University has made considerable contributions to the field of agent-based simulation of electricity markets. These contribution ranges from the analysis of market power to the analysis of agent learning (see also 3.1).

An overview of the EPRI Power market simulator developed at Iowa State University is presented by Nicolaisen (Nicolaisen et al. 2000). In the presented simulation distribution companies representing demand and generation companies take part in a double sided discriminatory auction. The matching algorithm matches the highest bids with the lowest asks and chooses the contract price as the midpoint of each matched bid and ask pair. Buyers are characterized by a buying capacity, a revenue per MWh sold to their costumers and fixed costs which are set to zero. Sellers are characterized by a maximum selling capacity, variable cost per MWh and fixed cost which are set to zero. Another feature of the model is the integration of grid constraints. Each agent is assigned a certain amount of available transmission capacity. The central goal of each agent is to maximize profits. Similar to the earlier work presented by (Richter and Sheblé 1998) a genetic algorithm for social learning is applied which is based on the profit of the last auction. In a case study the described model is used to assess the impact of relative concentration in terms of players and capacity on the market results. In the given experiment the hypothesis that market power is dependent on relative player or capacity concentration could not be supported, which is mainly ascribed to the simple genetic learning algorithm. As a consequence the use of an individual learning algorithm for a closer representation of real world behaviour is proposed.

An extension of the model is described by Nicolaisen et al. (Nicolaisen et al. 2001). One goal of the development is to provide a tool that helps to distinguish the effect of market structure and agent learning on market power in a simulation. For a closer representation of human behaviour a new learning algorithm is developed. The developed algorithm is a slight modification of the learning algorithm presented by Roth and Erev (Roth and Erev, 1995; Erev and Roth, 1998). It is a three parameter reinforcement learning algorithm that integrates the effect of experimentation and forgetting. The developed model is applied to test the impact of relative concentration on market outcomes. One tested hypothesis is that the overall aggregate profit of all market participants is nearly independent of market power effects. Again the impact of relative concentration could not be proven. However, the hypothesis on market efficiency in terms of overall profits shows some support but depends on the applied learning parameters.

A further agent-based simulation framework called AMES (Agent-based Modelling of Electricity Systems) is presented by Koesrindartoto et al. (Koesrindartoto and Tesfatsion, 2004; Koesrindartoto et al., 2005). The system is developed to allow intensive reliability and efficiency testing of the Wholesale Power Market Platform (WPMP) which has been proposed for common adoption by all U.S. wholesale power markets. The simulation model integrates the salient aspects of the WPMP, such as multi settlements (day-ahead and real-time) and locational marginal price (LMP) calculations. The transmission grid underlying the market is approximated by a DC optimal power flow problem with linearised constraints. The formulation of the tranmission grid representation is carefully described in (Sun and Tesfatsion 2006). The research focus of the AMES framework is the complex interplay among structural conditions, market protocols, and learning behaviours in relation to short-term and longer-term market performance.

2.4 Analysis of market design: Linking simulation models

A combination of several models with an agent-based simulation is developed in the Marketecture project carried out at Los Alamos National Laboratory (Atkins et al., 2004a; Atkins et al., 2004b). The model framework is made up by an urban population simulation, an agent-based market model and a grid model. The urban population model simulates individuals and locations of electricity demand. The results of the population simulation are used as an input for the model of the electricity market. The demand side is represented by buyer agents who buy electricity on behalf of the consumers. Electricity can be bought via bilateral trade and in a pool market. The supply side consists of single electricity generation units (generators) and sellers selling electricity on behalf of the generators. The main goal of the grid simulation is to integrate the restrictions to the market caused by the electricity grid. A central aspect of Marketecture is the analysis of the efficiency of the market mechanisms. Therefore the markets can be run in different order of execution and with different market mechanisms. The sellers acting on the market can be run with different trading strategies.

In the given case study the impacts of three different pool market clearing mechanisms (1. “normal” clearing, 2. Vickrey clearing, 3. Weighted average clearing) are analysed in combination with different trading strategies (1. competetive, 2. oligopolist, 3. competitive oligopolist). The speciality of the given approach is the combination of the agent-based electricity market simulation with a power flow model and a population simulation. Another aspect is the integration of several market clearing mechanisms. Consumers are randomly assigned to buyers. A central goal of the given development is to include individual behaviour in a market simulation without endangering the scalability of the model.

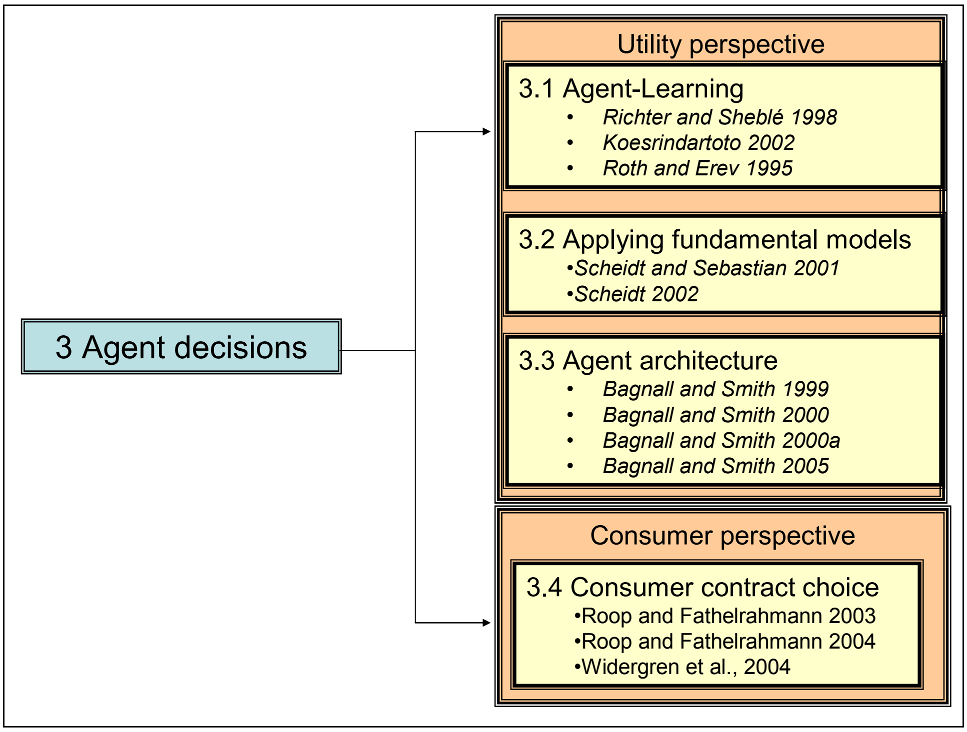
2.5 Summary

The analysed literature shows that agent-based simulation can be a useful tool to test market design. In the presented papers different market settings are tested. Among these are aspects like the order of market execution (Atkins et al., 2004a; Atkins et al. 2004b) or the market clearing. There is a common tendency to enlarge the scope of the simulation. Starting from rather simple models where the electricity demand is integrated by an aggregate demand curve new systems which integrate demand side bidding have evolved (Bunn and Oliveira, 2001). Another ongoing extension to the existing models is the integration of several markets (e.g. Bunn and Micola, 2005) and the use of external non-agent-based models providing additional functionality for the agent-based simulation (e.g. Atkins et al., 2004a). One remarkable difference between most European projects and the projects carried out in the US is the importance of a detailed simulation of the electricity grid. While a detailed integration of grid constraints seems to be a crucial aspect in the U.S. transmisison constraints are not integrated in most European projects. The ongoing development of increasing the scope of agent-based simulation of electricity markets also increases the requirements on the agents acting on these markets since the amount of information and coordination that has to be dealt with increases. A demanding task pointed out among others by Visudhiphan (Visudhiphan, 2003) is the validation of agent-based simulation since the required data on real bidding behaviour and market conditions are not available in most cases.

3 Models with focus on agent decisions and learning

This section presents three selected projects which provide some important contributions to the decision-making of agents in electricity markets. The work carried out at Iowa State University develops suitable learning algorithms for the analysis of the electricity market. While the work carried out at Pacific Northwest National Laboratory presents an approach to modelling consumer contract choice the research presented by Scheidt seeks to enhance the agent choices by the integration of conventional optimisation tools. A totally different way to improve agent-based simulation can be found in the work of Bagnall and Smith focussing on agent architecture and agent learning. An overview of the reviewed literature in this section is given in Figure 4.

Figure 4: Overview of reviewed papers on agent decisions



Source: (own visualisation)

In order to provide a basis for the discussion of different models dealing with agent-learning some important terms are explained in the following bullet points.

• Reinforcement learning: Agents interact with a dynamic system in a sequential process. Actions are selected to maximize a reward. The probability of successful strategies is increased. (see also (Moriarty and Schultz, 1999)

• Genetic algorithm: Genetic algorithms are orientated on the concept of evolution. The available strategy space is broken down into strategies consisting of small segments (genes), e. g. the volume bid into the market. Strategies are evaluated according to their fitness and successfull ones are selected and children (new strategies) are created by applying biological principles such as crossover and mutation to the genes. (see also Richter and Sheblé, 1998; Ortiz-Boyer et al., 2005)

• Learning classifier system: Learning classifier systems are rule based learning mechanisms which consist of three major components. 1. A production system which contains rules of action in a given environment (classifier). 2. A reinforcement method measuring the perform-ance of a rule 3. A rule discovery algorithm which creates new rules (see also Bagnall, 2000a, p.155ff.).

3.1 Analysis of the impact of agent learning on simulation results

An early development of an electricity market simulation is presented by Richter and Sheblé (Richter and Sheblé, 1998). Remarkable aspects of the described approach are the use of a genetic algorithm for social learning and the application of multiple bidding rounds for a one time period of electricity deliveries. After the initialization procedure each trading round starts with a price prediction which can be based on moving average, weighted moving average, exponentially weighted moving average or linear regression. Bids are calculated on the basis of the price prediction. Thereafter the auction takes place and is repeated as long as there is electricity to buy or to sell. In a next step the genetic algorithm selects the most profitable parents and replaces the least successful half of the population. Then the cycle is repeated with a new population. Richter and Sheblé describe a test application of the model where one distribution company represents a fixed electricity demand and 24 generators bid on the supply side. Grid constraints are neglected and all generators are characterized by the same generation cost curve (Richter and Sheblé, 1998).

In another case study Koesrindartoto (Koesrindartoto, 2002) analyses the impact of agent learning on market results. He uses a market simulator with buyers and sellers bidding on a market implemented as a discrete double auction. In order to show the impact of agent learning the market outcomes of bidding at marginal cost or revenue are compared to market results in a simulation where a Roth-Erev reinforcement learning algorithm (Roth and Erev, 1995) is applied with different parameter settings. The results show that the learning algorithm has considerable impact on market results and efficiency. The results also show that the parameter setting for the experimentation parameter of the applied learning algorithm influences the results considerably leading to the lower market efficiency in case of higher tendencies towards experimentation.

3.2 Application of fundamental models to support agent decisions

Another agent-based simulation project, this one focussing on the German electricity sector, has been carried out at the RWTH Aachen University (Scheidt, 2002; Scheidt and Sebastian 2001). In his PhD thesis Scheidt describes and implements an agent-based simulation of the German electricity sector which includes some new elements in comparison to the early work carried out at London Business School. New aspects are the simulation of a spot market and an OTC market. The spot market in the given project is modelled as a double-sided auction with a uniform-price settlement market clearing. The OTC market is executed after the spot market.

The described work puts special emphasis on the simulation of the trading preparation which is executed after the initialization phase. Thereby the generation of a load and price forecast play an important role. An interesting aspect of the described model is the use of non-agent-based tools for the provision of data within the agent-based simulation. The load forecast is based on historical data with a randomized error margin of 5% (Scheidt, 2002). The price prognosis can either be based on the method of floating average or an external tool called BoFIT-LP using artificial neuronal networks for the calculation of a price prognosis (Scheidt, 2002). Another important part of the simulation is the provision of data on the generation portfolio which can be either based on an external tool (BoFIT-TEP) for the optimal utilization of a plant portfolio or a merit order curve.

The simulation described by Scheidt is implemented in JAVA using the agent building toolkit ZEUS[3]. It is made up of agents with different roles, representing different functions in the electricity system. Roles within a utility comprise a pool trader and an OTC trader as well as auxiliary roles (price and load forecast, daily resource scheduling). Other roles comprise an auctioneer and a transmis-

3 For more information on ZEUS see http://sourceforge.net/projects/zeusagent

sion system operator. Although the integration of grid constraints for the calculation of local prices is discussed it is not implemented due to the lower importance in the German market. A central part of the simulation are the trader agents. In contrast to most other analysed models a trader agent in this model is capable of buying and selling electricity, depending on the utilisation of its power plants. The trader agents are driven by the two goals to increase their profits continuously and to ensure a given utilization of the generation of the portfolio. In order to reach their goals the trader agents are endowed with a rule-based algorithm which determines the bid price for the next period. Trading on the spot market is based on generation costs, expected profit margin and acceptable losses in order to ensure plant utilisation. Thereby acceptable losses and margin are part of a reinforcement learning algorithm. In the case of trading on the OTC market, spot market results are taken into consideration when determining the trading strategy.

The author presents short-term simulation results. The simulation is based on synthetic data and does not reflect the real situation of the German electricity market. Plant outages are not taken into account. Despite these simplifications the model results are similar to short term price developments on the German spot market. However, there are still some deviations from real market data and Scheidt points out that a realistic agent-based simulation can have extensive data requirements which can be difficult to satisfy especially as some of the data is proprietary (Scheidt, 2002).

3.3 Increasing realism by improved agent architecture

Bagnall and Smith present an agent-based simulation of the UK electricity market which considers the market rules in place before 2001. In contrast to the work carried out at London Business School the work presented by Bagnall and Smith has a stronger focus on the agent architecture (Bagnall and Smith, 2005). Agent learning and bidding strategies are key elements of their developed model. Similar to early stages of the other examples presented above the presented simulation focuses on the supply side of the electricity market with a given predicted load curve which is represented by typical load characteristics of winter and summer weekdays and weekends in winter and summer, respectively (Bagnall, 2000a). Deviations from forecast and real load are not taken into account. In contrast to some of the projects presented in this survey the given model has no physical load flow model of the transmission system. However, the model integrates unit commitment constraints, e.g. minimum and maximum generation levels for each generation unit (Bagnall and Smith, 2000). The market processes are structured in two steps: In a first round demand and supply are matched in an unconstraint schedule. Thereafter constraints are incorporated into the schedule and a capacity premium for grid balancing is calculated.

Since the agent architecture is the central part of the given project the structure of the agents is rather complex. Their strategy choices are driven by two main goals. The first goal is to avoid losses and the second goal is to maximize the profit. Both goals are represented by an own learning classifier system within the agent. The agent controller has a small memory containing a limited number of past experiences. Other elements of the agent are the detector and effector which are the link to the environment. The described model is applied in case studies to compare a pay as bid market clearing to a uniform market clearing (Bagnall and Smith, 2005) and the analysis of different constraint levels (Bagnall and Smith, 2000). Another important aspect of the case study is the analysis of agent behaviour which exhibits realistic bidding for generation units (Bagnall, 2000b), and a realistic market volatility (Bagnall and Smith, 2005).

3.4 Integration of the consumer perspective: Consumer contract choice

An interesting project with stronger focus on the consumer perspective in electricity markets is the work carried out at Pacific Northwest National Laboratory. Roop and Fathelrahmann describe a model which combines a distribution grid model with a contract choice model focussing on residential consumers (Roop and Fathelrahmann, 2003). In the cited article the consumer choice between fixed tariffs and time dependent tariffs is analysed. In order to simulate consumer contract choice a modified Roth-Erev learning algorithm is used. The consumer decision process is structured as follows. Every month the consumer agents receive their bills. In order to initiate further thought on contract choice the bill has to be higher than expected. The next hurdle is the actual difference between the expected bill and the actual bill. Only if the difference exceeds a certain value the consumer will seek for other contract options. Based on the available alternatives the consumer will calculate the expected savings. If the expected savings exceed a certain threshold the consumer updates his propensity to change contracts and eventually changes contracts if the propensity to change contracts reaches a threshold value. The propensity to change contract is also influenced by a forgetting parameter and an experimentation parameter which characterizes consumers. Due to the variety of parameters influencing the consumer contract choice the calibration of these parameters is an important issue. In the paper different parameter settings are analysed showing that the expected savings threshold seems to be the most important factor within the described model. The planned extension of the model seeks to integrate different consumer types, load serving entities and generators bidding on different markets (Roop and Fathelrahmann, 2004).

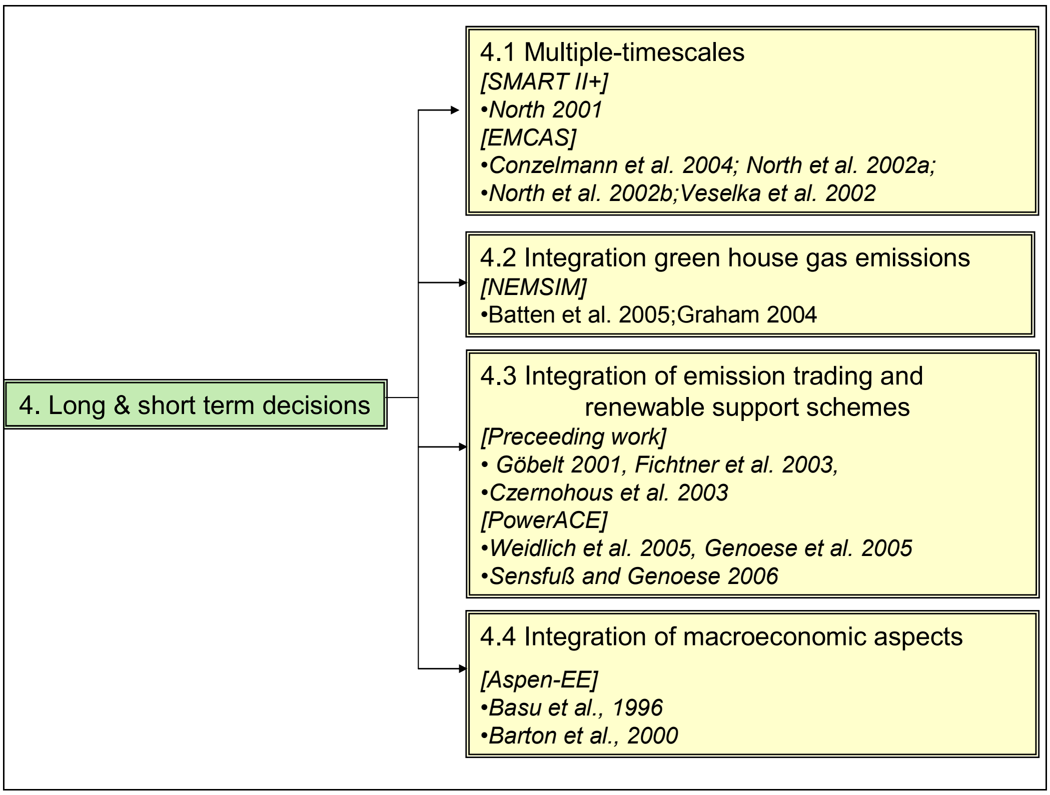
3.5 Summary

The examples above have contributed to the development of agent decisions in three different ways. The project carried out at Pacific National Lab integrates consumer contract choice into the simulation of electricity markets. In order to simulate this decision process a new algorithm is presented. The work presented by Scheidt shows that it can be useful to integrate conventional optimisation tools and forecasting tools based on neuronal networks to support agent decisions. Another possibility to enhance agent decision processes as presented by Bagnall and his colleagues is the improvement of agent architecture e.g. by the use of learning classifier systems which enable the agents to pursue more than one goal. The work presented by Koesrindartoto shows that the choice of the learning algorithm has a considerable impact on the results. A common tendency in recent work seems to be the use of individual learning algorithms instead of social learning.

4 Models for the coupling of long-term and short-term simulations

This section presents three selected projects which focus on the coupling of several short-term decisions and long-term decisions. In contrast to the models concentrating on short term markets these projects envisage the integration of a long-term perspective such as capacity expansion planning. In the analysed literature the proposed simulation platforms also include several markets in one simulation. One project in this field is carried out at the Argonne National Laboratory. The current work of the Fraunhofer Institute and the Universität Karlsruhe seeks to develop a model which is capable of integrating aspects related to emission trading and the expansion of renewable electricity generation as well as the long-term investment decisions of conventional power plants. Another project currently under development is the work carried out at CSIRO Australia which can draw on an extensive market database. A striking example for the possible integration of agent-based simulation into macroeconomic analysis is the Aspen-EE model developed at Sandia National Laboratories. An overview of the reviewed literature is given in Figure 5.

Figure 5: Overview of the reviewed literature in chapter 4



Source: (own visualisation)

4.1 Development of an agent-based simulation with multiple time scales

In North, 2001 an integrated long-term-model of the electric power and natural gas markets is presented, focussing on interdependencies between these markets. The model, SMART II+ consists of a set of agents and interconnections representing the electric power marketing and transmission infrastructure as well as the natural gas marketing and distribution infrastructure. Market participants are producers and consumers. Both producers and consumers have an initial investment capital, which can increase through profit and decrease through losses. Reaching a certain level of investment capital offers the possibility of purchasing additional production capacity or growing in form of new consumers. Natural gas fired electric generators derive their costs from the natural gas market. These generators are consumers in the natural gas marketplace. Main results are that natural gas fired electrical generators are highly competitive, which causes an increasing market share. A rising market share radically increases market interdependence, because both markets compete for the same underlying resource, natural gas.

An outgrowth of the early SMART II+ project which combines detailed modelling of the electricity grid with an agent-based simulation of power markets is the Electricity Markets Complex Adaptive System [EMCAS] developed at Argonne National Laboratory (Conzelmann et al., 2004). In addition to a spot market and a bilateral market for electricity EMCAS also simulates four markets for the grid regulation which represent the different levels of reserves ranging from the primary AGC regulation to the replace reserve.

In order to analyse the impact of different market pricing mechanisms EMCAS is able to simulate a uniform-price market clearing and a pay-as-bid pricing rule (North et al., 2002b). Another interesting aspect about EMCAS is that it is designed to simulate decisions on six different time scales ranging from real time dispatch of power plants to multi-year planning (Veselka et al., 2002). The electricity demand in EMCAS is represented by consumer agents who are supplied by demand companies. Consumer agents can switch their supplier or decrease electricity demand. Demand companies purchase electricity and sell it to consumers. The supply side of the model is represented by generation companies that own generators representing power plants and decide on bidding strategies and the operation of these plants. The grid operation is represented by transmission companies and distribution companies. Distribution companies operate and charge for the use of the distribution grid while transmission companies only charge for the use of the transmission system. The efficient operation of the transmission system and the different markets is the central task of the independent system operator/regional transmission provider (ISO/RTO). A special event generator can be used to simulate unforeseen developments like plant outages. The user can specify different market rules and parameters which are represented by the regulator agent.

Another remarkable aspect of EMCAS is the design of the agents with regard to decision processes and agent learning. Conzelmann describes the agents as “thick” agents due to their complexity (North et al., 2002a). They try to maximize a multi-objective utility function which includes risk preferences and other goals like minimum profit or market share (Veselka et al., 2002). The actual objectives vary depending on the agent. The objectives are represented by a minimum expected value, a maximum expected value and a risk preference. There are several activities carried out by a generation company. One important module is the generation of a price forecast which is based on the available information on the electric system and historical prices. Another module calculates the unit commitment on the available markets. This information is used to calculate the expected utility of a given strategy. Past experiences are used to determine new strategies. The agent learning concept in EMCAS is based on an individual learning algorithm seeking to integrate the concept of exploration-based learning and observation-based learning.

In the reviewed case studies EMCAS has been used to analyse the impact of various conditions on market prices. Among these are bidding strategies, the impact of grid limitations on market prices and the impact of different market clearing mechanisms.

4.2 Integration of emission calculations into a multi-time-scale simulation

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) develops an agent-based simulation with goals similar to the work carried out at Argonne National Lab. One similarity between EMCAS and NEMSIM is the goal to simulate decisions on different time scales reaching from plant dispatch to multi-year planning. Other similarities are the integration of a grid simulation and the trade on spot and OTC markets. In addition to the concept of EMCAS it is planned to integrate a green house gas emission calculator (Batten et al., 2005). Currently, the model is still under construction and to the knowledge of the authors, no results have yet been published for this simulation model. However, the model development can be based on information for six years of trading on the Australian electricity market (Graham, 2004).

4.3 Integration of investment decisions, CO_2-emission trading and renewable support schemes

Since 2000/2001 at the University of Karlsruhe and the Fraunhofer Institute of Karlsruhe several approaches of agent-based energy models have been designed. Among these are concepts presented by Göbelt (Göbelt, 2001) and Fichtner (Fichtner et al., 2003). These concepts seek to combine agent-based simulation with linear optimisation models. Another aspect proposed by Fichtner (Fichtner et al., 2003) is the integration of long term decisions such as investment into power plants. A more comprehensive simulation of electricity markets and the integration of long-term decisions is proposed by Czernohous et al. (Czernohous et al., 2003). In addition to investment planning it proposed to to use optimisation techniques also for plant dispatch and trade preparation which is similar to the work presented by Scheidt (Scheidt, 2002). A new aspect is the concept of a regulatory agent seeking to reduce emissions of harmful substances.

In 2004 a new project started in Karlsruhe: PowerACE. The aim of this project is to simulate the development of the German electricity and certificate market under the conditions of the liberalised electricity market as well as the promotion of renewable energy and the new CO_2-emission trading (see Weidlich et al. 2005, Genoese et al. 2005). Market players, like power generating companies or operators of renewable energy, are split into diverse agents (Weidlich et al., 2005) and each agent carries out one or more functions like plant dispatch or trading. On the demand side the consumer agents representing different sectors negotiate contracts with the supplier agents. The result of this negotiation process is that all consumers and their corresponding load profiles are assigned to suppliers by contracts. Based on the knowledge about their contracted load the suppliers purchase the required electricity on the power markets via buyers. The sellers generate bids according to their merit order curve including start-up cost of plants (Sensfuss and Genoese 2006). Renewables bid at zero price to simulate the guaranteed feed in according to the German Renewable Energy Sources Act (see also EEG 2004). The agent AuctioneerEEX matches the bids of the bidders using the European Energy Exchange Clearing mechanism (see also EEX 2005) and returns the results. Capacities can both be sold on the spot market and / or the balancing power market.

For long-term analysis, the development of the German power plant capacities is simulated. The power plant portfolio is updated once per year. At the moment capacity extension is realised via a soft link to the linear optimisation model PERSEUS-ZERT (see also Enzensberger, 2003). Endogenous investment decisions for renewable power plants and conventional power plants are modelled separately with the investment planner agent (Sensfuß et. al, 2006; Genoese et al. 2006). Decisions of this agent will modify the power plant portfolio and thus influence i.e. the short-term trading decision (Genoese et al., 2005). The model is implemented in Java and uses RePast, the Recursive Porous Agent Simulation Toolkit (North et al. 2006). In a case studies it is shown that the model is able to produce realistic spot market results on an hourly level (Sensfuss and Genoese, 2006). In another case study the model is used to assess the CO2-savings by renewable energy sources (Genoese et al., 2005).

In (Weidlich and Veit 2006) the interplay between a day-ahead market market for physical delivery contracts and a day-ahead minute reserve market is analysed. Generators are modelled as adaptive agents that apply an Erev-Roth type reinforcement learning algorithm. At any one market, generators integrate opportunity costs that arise from the foregone opportunity of selling their capacity in the other market into their reinforcement. The authors find that the order of market execution influences prices on both markets. On the spot market, supply side concentration has a major impact on resulting prices, i.e. high generator competition leads to lower prices. On the balancing power market opportunity costs have a stronger influence on bidding decisions. Thus, prices tend to be higher on the balancing power market when physical delivery prices are high. For that reason, prices on both markets are lower when the spot market is executed first, because all generators can bid their entire capacity there, resulting in high competition. When the spot market is executed second, some generators have already committed capacity on the balancing power market, which results in less competition and thus higher prices. This, in turn, increases opportunity costs when bidding in the balancing power market, which raises prices on this market, too.

4.4 Integration of macroeconomic aspects

The agent-based simulation called Aspen-EE developed at Sandia National Laboratories seeks to analyse the impact of market structures and power outages in the electricity sector on the economy (Barton et al., 2000). In addition to the ability to model several power markets it simulates the labour market and the product market. The electricity demand is modelled with industry, household and commercial agents. Besides their common task to purchase and consume electricity, the agents carry out other functions such as producing goods or paying taxes. In addition to the common agents in an electricity market simulation, i.e. generation companies and an independent system operator, a fuel company agent is introduced which sells fuel to the generation companies. The infrastructure of the simulation is supported by a bulletin board for public information, a disaster agent and weather agent determining power outages and demand development. The price setting of the agents is based on a genetic learning classifier system [GLACS] (see also Basu et al., 1996). While commercial agents and fuel company agents are charged a fixed price for electricity, industry agents actively bid on the market. The government agent collects taxes and pays unemployment benefit. During power outages perishable goods decay and work productivity is reduced. In a case study the capabilities of the model are shown in a model run with two markets in order to analyse the impact of price caps.

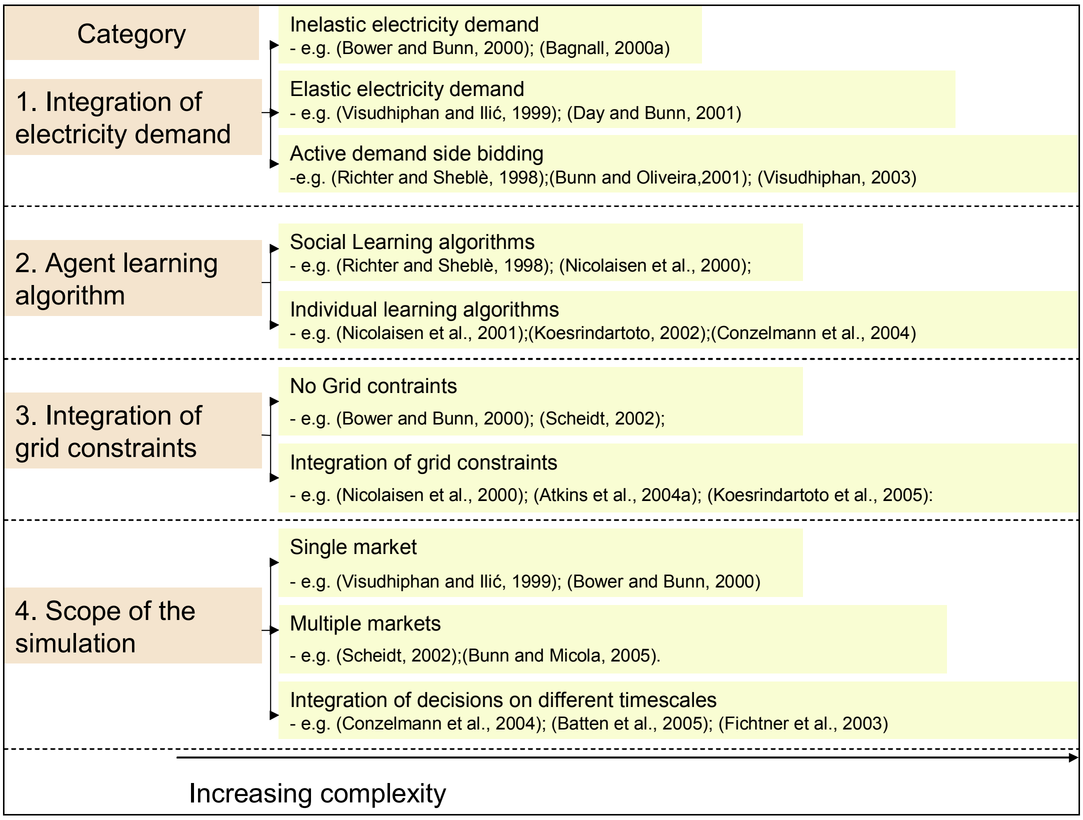
4.5 Summary

The projects presented above are very complex in their scope. Proposed aspects are the coupling of several markets like spot market and balancing power markets. In order to be able to trade successfully on several markets the agents involved in the simulation tend to become more complex. Another factor increasing the complexity of the discussed models is the integration of aspects like consumer contract choice and investment. Since the decisions take place in different time horizons the coordination of agents acting on different time scales within the simulations is necessary. In order to provide realistic results the discussed models require extensive data ranging from information on corporate details concerning demand load curves as well as precise power plant data. Although the models discussed above are still under development first simulation runs of EMCAS and PowerACE show that the development of these large scale projects is on its way.

5 Conclusions

Although the concept of agent-based simulation of electricity markets is a rather new development the reviewed literature shows considerable progress in the development of different simulation models within the last five years. Starting from simple models with aggregated demand curves and few supply bidders on one market the development has continued to concepts of large scale simulation platforms which are capable of dealing with multiple markets and time scales. An overview of the developments in four selected categories with examples of the reviewed literature is given in Figure 6.

Figure 6: Examples for the increasing complexity of agent-based simulations



Source: (own visualisation)

However, the development of an agent-based simulation of electricity markets is a demanding task. There are several challenges to the development of agent-based simulations. A first issue is the development of an adequate agent architecture and the use of suitable learning algorithms since experiences of recent projects have shown that the learning algorithm has considerable impact on the results (Koesrindartoto, 2002). Another important issue is the provision of data as a basis for agent decisions. Thereby the use of conventional models e.g.

optimsation models for the utilisation of the plant portfolio as a source of data for agent decisions has been successful (Scheidt, 2002). A difference between most developments in the USA and Europe is the importance of the integration of grid constraints. While the integration of grid constraints is a crucial issue to most projects carried out in the USA it is less important in most European projects focussing on national markets due to the differences in the existing infrastructure. However, rising electricity demand and the integration of large scale offshore wind energy also raises grid issues in Europe (DENA, 2005).

As the concept of agent-based simulation is applied to large scale simulation platforms models such as EMCAS, PowerACE or NEMSIM the requirements on the data and agent architecture increase considerably ranging from detailed electricity market and load data to future power plant options. Thereby it has to be stated that a common challenge to all agent-based simulations in electricity markets is the validation of simulation results. In the reviewed literature market outcomes are compared to real-world market data e.g. with respect to market prices. Another issue is the validation of the behaviour of single agents which is a demanding task in itself. Thereby the analysis of agent decisions such as consumer contract choice or investment decisions may require considerable efforts to improve the empirical data basis. Despite all the challenges first attempts to compare market results of agent-based simulation with real-world data are promising (Sensfuß and Genoese, 2006; Scheidt, 2002). The results of the reviewed literature show that the concept of agent-based simulation as a test bed for the electricity sector can provide additional insights for market and policy design.

References

Atkins, K., C. Barret, C.M. Homa, A. Marathe, M. Marathe and S. Thite (2004a) ‘Marketecture: A simulation based framework for studying experimental deregulated power markets.” http://citeseer.csail.mit.edu/atkins04marketecture.html, downloaded 01.06.2005

Atkins, K., C. Barret, C.M. Homa, A. Marathe, M. Marathe and S. Thite (2004b) ‘Agent Based Economic Analysis of deregulated electricity markets.’ 6th IAEE European Energy Conference on ‘Modelling in Energy Economics and Policy’, Zürich

Bagnall, A.J. and G.D. Smith (1999) ‘An adaptive agent model for generator company bidding in the UK power pool.’ *Lecture Notes in Computer Science 1829*, 191-203.

Bagnall, A.J. (2000a) ‘Modelling the UK market in electricity generation with autonomous adaptive agents.’ PhD Thesis, University of East Anglia, 2000.

Bagnall, A.J. (2000b) ‘A Multi-Adaptive Agent Model for Generator Company Bidding in the UK Market in Electricity.’ Genetic and Evolutionary Computation Conference (GECCO-2000), 605-612.

Bagnall, A.J. and G.D. Smith (2000) ‘Game playing with autonomous adaptive agents in a simplified economic model of the UK market in electricity generation.’ Proceedings of IEEE-PES / CSEE International conference on power system technology (Powercon 2000), Perth, Australia, 2000.

Bagnall, A.J. and G.D. Smith (2005) ‘A Multi-Agent Model of the UK Market in Electricity Generation’ IEEE Transactions on Evolutionary Computation, in press, to appear August 2005. http://www.sys.uea.ac.uk/~ajb/PDF/IEEE_TEC05.pdf, downloaded 28.06.2005

Bakay, Z., Schwaiger, M. (2004a) ‘Kundenbindung von privaten Stromkunden – Ermittlung zentraler Treiber’, *Energiewirtschaftliche Tagesfragen*, 1:2:22-25.

Barton, D.C., E.D. Eidson, D.A. Schoenwald., K.L. Stamber and R.K. Reinert (2000) 'Aspen EE: An Agent-based Model of infrastructure interdependency.' http://www.cs.sandia.gov/web9216/pubsagent/Aspen_EE.pdf, downloaded 01.07.2005

Basu, N., R.J. Pryor, T. Quint and T. Arnold (1996) 'Aspen a microsimulation model of the economy.' http://www.cs.sandia.gov/web9216/pubsagent/Aspen_Paper2.pdf downloaded 01.07.2005

Batten, D., G. Grozev, M. Anderson and G. Lewis (2005) 'NEMSIM: Finding ways to reduce greenhouse gas emissions using multi-agent electricty modelling.' Draft Working Paper, http://smaget.lyon.cemagref.fr/contenu/SMAGET%20proc/PAPERS/Batten.pdf, downloaded 01.07.2005

Bower, J. and D.W. Bunn (2000) 'Model-Based Comparisons of Pool and Bilateral Markets for Electricity.' *The energy journal* 21:3:1-29.

Bower, J. and D.W. Bunn (2001) 'Experimental analysis of the efficiency of uniform-price versus discriminatory auctions in the England and Wales electricity market.' *Journal of Economics Dynamics & Control* 25:561-592.

Bower, J., D.W. Bunn and C. Wattendrup (2001) 'A model based analysis of strategic consolidation in the German electricity industry.' *Energy Policy* 29:12 987-1005.

Bunn, D.W. and C.J. Day (2002) 'Computational Modelling of price-formation in the electricity pool of England and Wales.' EMG Working Paper, 2002. http://www.london.edu/assets/documents/PDF/2.3.4.12.1_Bunn_and_Day_2003_pdf6.pdf, downloaded 22.08.2005.

Bunn, D.W. and F.S. Oliveira. (2001) 'Agent-Based Simulation: An Application to the New Electricity Trading Arrangements of England and Wales', IEEE – TEC on Evolutionary Computation, special issue: Agent Based Computational Economics: 5:5 493-503.

Bunn, D.W. and F.S. Oliveira (2003) 'Evaluating Individual market power in electricity markets via agent-based simulation.' *Annals of Operations Research* 121: 57-78.

Bunn, D.W. and M. Martoccia (2005) 'Unilateral and collusive market power in the electricity pool of England and Wales.' *Energy Economics* 27:2: 305-315.

Conzelmann, G., M. North., G. Boyd, R. Cirillo, V. Koritarov, C. Macal, P. Thimmapuram and T. Veselka (2004) 'Agent-Based Power Market Modelling: Simulating strategic market behaviour using an agent-based modelling approach.' 6th IAEE European Energy Conference on Modelling in Energy Economics and Policy, Zürich. http://www.saee.ch/saee2004/Conzelmann_North_Boyd_etal.pdf, downloaded 10.08.2004.

Czernohous, C., W. Fichtner, D. Veit, and C. Weinhardt. (2003) 'Management decision support using long term market simulation.' *Journal of Information Systems and e-Business Management* (ISeB) 1(4): 405-423.

Day, C.J. and D.W. Bunn (2001) 'Divestiture of Generation Assets in the Electricity Pool of England and Wales: A Computational Approach to Analyzing Market Power.' *Journal of Regulatory Economics* 19:2: 123-141.

DENA (2005) 'Planning of the Grid Integration of Wind Energy in Germany Onshore and Offshore up to the Year 2020 (dena Grid study).' http://www.dena.de, downloaded 10.06.2005.

Drogoul, A., D. Vanbergue and T. Meurisse (2002) 'Multi-Agent Based Simulation: Where are the Agents?' Proceedings of MABS'02 (Multi-Agent Based Simulation, Bologna, Italy, July 2002), LNCS, Springer-Verlag

EEG 2004. 'Gesetz zum Vorrang erneuerbarer Energien, Renewable Energy Sources Act.' http://217.160.60.235/BGBL/bgbl1f/bgbl104s1918.pdf, downloaded 21.08.2005.

EEX 2005. 'Das Spotmarktkonzept.' http://www.eex.de/info_center/downloads/dl_spot/booklet.pdf, downloaded 21.08.2005.

Enzensberger, N. (2003) 'Entwicklung und Anwendung eines Strom- und Zertifikatmarktmodells für den europäischen Energiesektor.' Dissertation. University of Karlsruhe.

Erev, I., and A.E. Roth (1998) 'Predicting how people play games: Reinforcement Learning in Experimental Games with unique mixed strategy equilibria.' *The American Economic Review* 88: 848-881.

Ernst, D., A. Minoia and M.D.Ilić (2004) 'Market Dynamics Driven by the Decision-Making Power Producers', Proceedings of Bulk Power System Dynamics and Control, Cortina D'Ampezzo, Italy

Fichtner, W., D. Möst, M. Wietschel, C. Weinhardt and O. Rentz (2003) 'Zur strategischen Planung bei Energieversorgern in liberalisierten Energiemärkten'. *WiSt - Wirtschaftswissenschaftliches Studium* 32:12: 707-713.

Franklin, S. and A. Graesser (1997) 'Is it an agent or just a program? A taxonomy for autonomous agents.' In *Intelligent Agents III: Agent Theories, Architectures, and Languages*, Ed. J. Müller, M. Wooldridge, and N. Jennings, ECAI96Workshop Proceedings: 21-35.

Genoese, M., F. Sensfuß, A. Weidlich, D. Möst and O. Rentz (2005): 'Development of an agent-based model to analyse the effect of renewable energy on electricity markets', in: Proceedings of the 19th Conference 'Informatics for Environmental Protection' (EnviroInfo). Brno.

Gilbert, N. and S. Bankes (2002) 'Platforms and methods for agent-based modelling,' *Proceedings of the National Academy of Sciences*. 99:3: 7197–7198.

Göbelt, M. (2001) 'Entwicklung eines Modells für die Investitions- und Produktionsprogrammplanung von Energieversorgungsunternehmen im liberalisiserten Markt.' Dissertation, University of Karlsruhe

Graham, H. (2004) 'Energy Transformed Flagship energy futures theme.' Presentation CSIRO Climate Science Meeting," http://www.dar.csiro.au/csiroclimate/Docs/Graham.ppt, downloaded 01.07.2005.

Klemperer, P.D., and M.A. Meyer. (1989) 'Supply Function Equilibria in Oligopoly Under Uncertainty.' *Econometrica* 57:11: 1243-1277.

Koesrindartoto, D. (2002): 'Discrete Double Auctions with Artificial Adaptive Agents: A Case Study of an Electricity Market Using a Double Auction Simulator', Department of Economics Working Papers Series No 02005.

Koesrindartoto, D. and L. Tesfatsion L. (2004) 'Testing the reliability of FERC'S Wholesale Power Market Platform: An agent-based computational economics approach.' In Proceedings of USAEE/IAEE North American Conference, Washington D.C. July 8-10. http://www.econ.iastate.edu/tesfatsi/usaeetalk.pdf, downloaded 04.07.2005.

Koesrindartoto, D., J. Sun and L. Tesfatsion (2005) ‘An agent-based computational laboratory for testing the economic reliability of wholesale power market designs.’ Proceedings of IEEE Power Engineering Conference, San Francisco: 931-936.

Mangina, Eleni (2002): ‘Review of Software Products for Multi-Agent Systems’, Software Report, AgentLink II

Micola, R.A., A. B. Estañol, D.W. Bunn (2006) ‘Incentives and Coordination in Vertically Related Energy Markets.‘ CIC Working Papers, No. SP II 2006-02.

Moriarty, D. E.; Schultz, A. C. (1999): Evolutionary algorithms for reinforcement learning. In: Journal of Artificial Intelligence Research, 11 ((1999)), pp. 241-276

Nicolaisen, J., M. Smith, V Petrov and L. Tesfatsion (2000) ‘Concentration and capacity effects on electricity market power.’ Proceedings of Congress on Evolutionary Computation, La Jolla (USA): 1041-1047.

Nicolaisen, J., V. Petrov, L. Tesfatsion (2001) ‘Market Power and Efficiency in a computational electricity market with discriminatory double-auction pricing’ ISU Economic Report No. 52, 2000, revised 2001. http://www.econ.iastate.edu/tesfatsi/mpeieee.pdf, downloaded 10.05.2005.

North, M. (2001) ‘Multi-Agent Social and Organizational Modeling of Electric Power and Natural Gas Markets’, *Computational & Mathematical Organization Theory* 7: 331–337.

North, M., G. Conzelmann, V. Koritarov , C. Macal, T. Prakash and T. Veselka (2002a) ‘E-Laboratories: Agent-based modelling of electricity markets.’ Conference American Power conference 2002. http://www.dis.anl.gov/msv/cas/Pubs/APC-EMCAS.PDF, downloaded 14.08.2004.

North, M., C. Macal, G. Conzelmann, V. Koritarov, P. Thimmapuram and T. Veselka (2002b) ‘Multi-Agent Electricity Market Modeling with EMCAS.’ http://www.dis.anl.gov/msv/cas/Pubs/CASOS-EMCAS.PDF, downloaded 14.08.2004.

North, M., N.T. Collier and J.R. Vos (2006) ‘Experiences Creating Three Implementations of the Repast Agent Modeling Toolkit’ *ACM Transactions on Modeling and Computer Simulation* 16:1: 1–25.

Ortiz-Boyer, D.; Hervas-Martinez, C.; Garcia-Pedrajas, N. (2005): A crossover operator for evo-lutionary algorithms based on population features. In: Journal of Artificial Intelligence Re-search, 24 (2005), pp. 1-48.

Price, C.W. (2003) Spoilt for Choice? The Costs and Benefits of Opening UK Residential Energy Markets, British Institute of Energy Economics (BIEE), http://www.biee.org/ downloads/conferences/Waddams%20Price.pdf, download 07.03.2006.

RePast, the Recursive Porous Agent Simulation Toolkit: http://repast.sourceforge.net

Richter, C.W. and G.B. Sheblé (1998) 'Genetic algorithm evolution of utility bidding strategies for the competitive market place.' *IEEE Transactions on Power Systems* 13:1:256-261.

Roop, J.M. and E. Fathelrahman (2003) 'Modelling Electricity Contract Choice: An agent-based approach.' Summer Study for energy efficiency in industry, New York. http://gridwise.pnl.gov/docs/pnnl38282.pdf, downloaded 29.07.2005.

Roop, J.M. and E. Fathelrahman (2004) 'Modelling the Distribution Utility as an agent in the wholesale market, Presentation.' IAEE Conference, 2004, Washington.
http://www.iaee.org/documents/washington/Joseph_Roop.pdf, downloaded 29.07.2005.

Roth, A.E. and I. Erev (1995) 'Learning in Extensive-Form Games: Experimental Data and Simple Dynamic Models in the Intermediate Term.' *Games and Economic Behaviour,* 8:164-212.

Scheidt, M. (2002) 'Ein Modell zur Mikrosimulation des Spothandels von Strom auf der Basis eines Multi-Agenten-Systems.' Dissertation RWTH Aachen.

Scheidt, M. and H.J. Sebastian (2001) 'Simulating Day-ahead trading in electricity markets with agents.' In proceedings of the Second Asia-Pacific Conference of International Agent Technology (IAT-2001), Japan, 2001. http://www.procom.de/en /products/bofit/publications/ maebashi_procom.pdf, downloaded 01.07.2005.

Sensfuß, F.; Genoese, M. (2006) ‘Agent-based simulation of the German electricity markets-An analysis of the German spot market prices in the year 2001-.’ Proceedings of the ‘9. Symposium Energieinnovationen’, 15-17.02.2006 Graz, Austria.

Sun, J. and L. Tesfatsion (2006) ‘DC Optimal Power Flow Formulation and Solution Using QuadProgJ.’ ISU Economics Working Paper No. 06014.

Tesfatsion, Leigh (2006) ‘Agent-Based Computational Economics: A Constructive Approach to Economic Theory.’ In *Handbook of Computational Economics*, Volume 2: Agent-Based Computational Economics, Ed. K. L. Judd and L. Tesfatsion, North-Holland.

Tobias, R. and T. Hofmann (2004) ‘Evaluation of free Java-libraries for social-scientific agent-based simulation.’ *Journal of Artificial Societies and Social Simulation* 7:1:, http://jasss.soc.surrey.ac.uk/7/1/6.html.

US-Canada Power System Outage Task Force (2004) ‘Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations.’ https://reports.energy.gov/BlackoutFinal-Web.pdf, downloaded 01.08.2005.

Ventosa, M., A. Baillo; A. Ramos and M. Rivier. ‘Electricity market modeling trends.’ Energy Policy (33): 897-913.

Veselka, T., G. Boyd, G. Conzelmann, V. Koritarov, C. Macal, M. North, B. Schoepfle and P. Thimmapuram, (2002) ‘Simulating the behaviour of electricity markets with an agent-based methodology: The Electricity Market Complex Adaptive Systems (EMCAS) Model.’ http://www.dis.anl.gov/msv/cas/Pubs/IAEE.pdf, downloaded 12.08.2004.

Visudhiphan, P. and M.D. Ilìc (1999) ‘Dynamic game based Modeling of electricity markets.’ 1999 IEEE PES Winter Power Meeting Proceeding, New York City, New York., 275-281.

Visudhiphan, P. and M.D. Ilìc (2001) ‘An Agent-Based Approach to Modeling Electricity Spot Markets.’ Proceedings of IFAC Modeling and Control of Economics Systems 2001 Meeting, Klagenfurt, Austria.

Visudhiphan, P. and M.D. Ilìc (2002) ‘On the Necessity of an Agent-based Approach to Assessing Market Power in the Electricity Markets’, Proceedings of the International Symposium on Dynamic Games and Applications, Sankt-Petersburg, Russia

Visudhiphan, P. (2003) ‘An agent-based approach to modelling electricity spot markets.’ Dissertation Massachusetts Institute of Technology.

Weidlich, A., F. Sensfuß, M. Genoese and D. Veit, (2005) ‘Studying the effects of CO_2 emissions trading on the electricity market – A multi-agent-based approach.’ Proceedings of the 2nd Joint Research Workshop ‘Business and Emissions Trading’, Wittenberg.

Weidlich, A. and D. Veit (2006) ‘Bidding in Interrelated Day-Ahead Electricity Markets – Insights from an Agent-Based Simulation Model.’ Proceedings of the 29th IAEE International Conference, Potsdam.

Widergren, S.E., J.M. Roop and Z. Huang (2004) ‘Simulating the dynamic coupling of market and physical system operations.’ IEEE General Meeting. 06-10.06.2004. Denver. http://gridwise.pnl.gov/docs/pnnl40415.pdf.

Wooldridge, M.and N.R. Jennings (1995) Intelligent Agents: Theory and Practice. In: Knowledge Engineering Review, 10 (2), pp. 115-152.

Wooldridge, M. (2002) *An Introduction to MultiAgent Systems*, John Wiley & Sons, Chichester.

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