Agent-based Computational Economics in Power Markets – Multi-agent Based Simulation as a Tool for Decision Support*

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Abstract. The aim of this research in progress is to examine the effect of CO_2-emission trading and the intensified application of renewable energy sources to the liberalized power market. The research approach applies methods from a combination of economics, natural sciences and computer science in order to obtain decision support for the planning of future power plant structures, investment decisions, and emission scales.

Besides the liberalization, future power markets are increasingly influenced by regulatory acts which are mainly responding to the necessity of a structured reduction of CO_2-emissions. For CO_2-eminssions, which are generated by the production of electric power, an emission trading system with obligatory participation is being launched from 2005 on. Since in the same period, the amount of power which has to be produced from renewable energy sources is increased dramatically, an additional incoming aspect is the fluctuating character of many of those sources.

These changed general conditions in the industrial power sector cause novel structures at international power markets and additionally a new emissions situation. The aim of this research is the conception of a methodologically innovative concept to simulate power markets based on multi-agent systems (MAS) and agent-based computational economics (ACE) which fulfils the described desiderata.

Since heterogeneous utility functions for individual market participants can be modelled – in comparison to existing centrally steered simulation methods – a multi-agent based simulation approach promises more realistic simulation results. Specific behaviour and the dynamic adoption of the strategies of individual participants based on the experiences derived from market behaviour can explicitly be simulated. The aim of the research approach is to obtain a strengthened understanding of the mutual effects among heterogeneous participants and the dynamics of the market of CO_2-emissions as well as renewable energy resources. To disseminate these results, acting recommendations for participants at international power markets as well as political and regulatory authorities are derived.

Keywords: Power Markets, Renewable Energy, Agent-based Computational Economics (ACE), Multi-Agent Systems (MAS), Simulation.

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1 Introduction and Aims of Research

1.1 Motivation

Motivated by the possible consequences of a global temperature increase which is partly based on anthropogenic generated climate relevant greenhouse gases climate protection is currently in the center of the discussion in environmental policy. At international level, United Nations have committed to a reduction of six mayor greenhouse gases[1] of 8 % until the timeline of 2008 – 2012 compared to emission level of 1990. These targets were formulated at the United Nations Framework Convention on Climate Change (UNFCCC) in Rio de Janeiro (1992) as well as the protocol accepted at the third conference of the parties in Kyoto (COP3). Within the so called EU burden sharing these 8 % (about 340 Bill. t of CO_2 equivalents) were allocated to the individual countries of the EU. An actual status report (Gugele 2001) shows that most EU countries as well as the over-all EU are far away from reaching this target.

Recently, based on actual emission developments in many European countries, the European Commission released a green book concerning an Europe wide harmonized trade of emission certificates. Based on this green book, a suggestion for an EU directive and its implementation has been worked out. Although strongly discussed, EU Environment Ministers Council released the implementation plan for emission certificate trading in early December 2002 (w.a. 2002) which is planned to take effect in the year 2005. By the induced reduction of a good which was free until now, the possibility to emit greenhouse gases into atmosphere reaches – from economic point of view – the status of a production factor. From this reduction of a formerly free product a pricing process is induced. The aim of this pricing is the adoption of planning processes within energy intense domains. These do not only provide implications on CO_2-emissions but also on other air pollutant[2]. However, strengthened by certificate trading, local emissions may – compared to a CO_2-emission reduction without certificate trading – drastically rise.

In case future climate politically motivated changes at the electricity market are regarded, fluctuating and renewable energy sources like wind and potovoltarics will play a key role. Under the assumption that these energies are especially supported in future years, different prognoses find that until 2025 in Germany wind energy plants with a capacity of 30 to 50 GW could be installed. This is equivalent to about 50% of the entirely installed capacity of electricity production in Germany. The effects of this development towards the electricity market regarding the power plant structures (amongst others backup plants, regular energy amounts, transport and distribution power lines, power prices) and the effects on CO_2-emission certificate trading are very strong (Ehrhart 2003). Furthermore, the question rises, how the subsidization of renewable energies can be combined with a system of emission certificate trading.

Methods from Operations Research (OR) and System Analytics are often applied in order to analyze the impact of climate political instruments on the planning and investment decisions of the concerned market participants such as energy supply companies, energy intense industrial branches or investors of wind farms. However, in this analysis the behaviours of the market participants on a competitive market are modelled only partial since alternative objectives of the participants are neglected.

Hence, from this discussion the necessity rises to develop methodologically novel approaches for market simulation of the European power market. This is in order to model the decision processes of all groups participating in the market more detailed and in this way to quantify the effects of the implementation of a Europe wide emission trading as well as the large-scale input of fluctuating energy resources in a better way.

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1 Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), partly halogenated chlorofluorocarbons (H-FKW), perfluorinated hydrocarbons (FKW) and sulfur hexafluoride (SF_6).

2 Based on the increased usage of gas, CO_2-reduction mostly entails a significant lowering of SO_2 emissions as well as a moderate reduction of NOx emissions.

1.2 Objectives

In order to achieve CO_2 reduction obligations e.g. according to the EU burden sharing targets substantial changes in the energy systems towards innovative and efficient production technologies are necessary. However, such a conversion process demands strategic decisions concerning innovations, which are connected with entrepreneurial risks. Besides market liberalization the necessities of a reduction of CO_2-emissions and the expansion of the use of renewable energies cause two more restrictions, which have to be considered in investment planning in the energy sector. Different participants will react with different strategies in taking risks and developing technical innovations under the modified framework conditions. However, the resulting participant-specific behaviour will be vital for the conversion of the energy systems. The different participants will influence each other and will modify their strategies continuously.

Due to the fact that so-called multi-agent systems are suited to model markets with the characteristics mentioned above it is the objective of this research project to simulate the development of the European electricity market based on this new modelling concept. With the help of a multi-agent system the effects of the liberalised energy market, the European emission trading scheme and the integration of fluctuating energy sources will be analysed. The multi-agent system shall be able to evaluate the European emission trading scheme with regard to its ecological efficiency and ecological effectiveness. Furthermore, conclusions about adjustments of the European emission trading scheme and the promotion of renewable energies will be drawn.

These objectives will be achieved with the help of a multi-agent system to simulate the liberalised electricity market in Germany considering the relevant neighbour-states for a time horizon between 20 and 30 years The different market participants will be modelled as autonomous units (autonomous software agents), which operate and communicate autonomously within the electricity market. Whereas the modelling of conventional technologies is state-of-the-art in optimising energy models, the problem of modelling plants with fluctuating energy production (like wind energy converters) is not yet solved. Therefore another objective of this research project is to integrate these plants into the simulation model. Thereby the exact characterisation as well as the modelling and prediction of fluctuations of renewable energies is of crucial importance.

2 Methodologies

2.1 Decision Support by Using Energy Models

For the elaboration of decision support in the energy sector, optimizing energy models have been subsequently designed and applied since the 1970s. These models can be differentiated into bottom-up models and top-down models (w.a. 1999). The main advantage of bottom-up models is the possibility to depict individual technologies. On the other hand, bottom-up models have the disadvantage that they neglect the economic cycle of production and usage of goods and services. Thus, effects on economic growth and employment cannot be modelled. Inverse advantages and disadvantages can be found in top-down models.

Bottom-up models are based on a detailed representation of energy conversion technologies and the interconnecting flows of energy (i. e. electricity and heat) and material (i. e. primary energy carriers, emissions of pollutants and greenhouse gases). The complete energy sector – starting from the resources via several energy-conversion steps up to the supply of final energy – is modelled in a consistent approach. Technologies and flows are characterised by technical (e. g. efficiency, lifetime), economic (e. g. investment, fixed and variable costs) and environmental (emission factors) parameters. Emissions resulting from electricity and heat generation as well as from distribution of energy carriers (e. g. natural gas) are calculated. Restrictions on the resulting emissions can be imposed on individual or cumulated emission levels. By comparing model results in scenarios with and without emission ceilings emission reduction strategies can be elaborated. The models usually employ a mixed-integer linear programming approach (see e.g. the PERSEUS model or the EUDIS model (Kreuzberg 1999; Wietschel 1999)) or a system dynamics approach (see e.g. (Grobbel 1999)).

In bottom-up models, possible technical reduction options are represented, making it possible to consider the interdependencies between individual measures. For example, the cost-efficiency of the rational use of electricity depends on the structure of the electricity supply system. If structural changes of the system (e. g. due to a switch from coal to gas or renewable energy carriers) lead to half the CO_2-emission factor for end use electricity, the emission reduction caused by the rational electricity use project will be halved.

In the context of this research project the advantages of optimizing energy models - with their all-encompassing target function negating alternative goals for different market players - will be combined with the advantages of multi-agent systems – with their agents acting autonomously.

2.2 Multi-Agent Systems and Simulation

A software agent or autonomous agent in the sense of the research community of Distributed Artificial Intelligence (DAI) is a piece of software that represents a participant and acts in its place. Software agents provide the following capabilities in full or in part. See also (Ferber 1999; Weiss 1999).

- Relation towards a function: i.e. they act within a specific domain.
- Locality (knowledge, data): i.e. they consider a specific situation
- Social behaviour: i.e. they communicate with other users and other agents.
- Autonomy: i.e. they autonomously search for negotiation counterparts and other agents.
- Reactivity on their environment: i.e. they monitor their environment and derive certain actions.
- Rationality: i.e. they maximize an individual utility function or preference rule.
- Adaptivity: i.e. they are able to adapt to new circumstances and learn from their results.
- (Mobility: i.e. they are able to move to other servers and continue working there.)

A set of two or more software agents are called multi-agent system. Based on above listed properties, the agents within a MAS provide the following properties: Interaction with their environment, autonomous acting, reactivity towards other agents, proactiveness, social behaviour in understanding and communication, rationality as well as adaptivity. These properties allow a modelling of distributed problem solving processes in a realistic way. The paradigm of multi-agent systems, originally stemming from computer science and DAI is applied now increasingly in economic research (Jennings 1998; Kirn 2002; Veit 2003).

Based in its scalability, the anatomy of the individual software agents as well as the flexibility in the generation of role profiles, multi-agent systems are predestined to model and simulate market based coordination problems. Here, role profiles are defined based on a classification of market participants into groups, where each group obtains a specific role. Since several years, multi-agent systems are applied to model real markets as well as to simulate markets and future market developments. Two prominent platforms have been established on which this topic is addressed: The Workshop und Agent-based Simulation (Urban 2000; Urban 2001) and the Workshop on Multi-agent Based Simulation (Sichman 1998; Moss 2001), bi-yearly held at the conference on Autonomous Agents and Multi-agent Systems (AAMAS). First approaches and models for the simulation of the German and English power markets exist (Bower 2000; Bunn 2001). These approaches solely focus the short-term horizon – long-term simulations have not been launched so far. In these approaches, the market situation under changed general conditions since the deregulation is addressed. In case of the German market, a simulation model has been developed. In the case of the English market a simulation model as well as an agent-based simulation environment. In the papers cited above, a simple reinforcement-learning approach is applied, using that the agents learn how to trade under consideration of auction rules. The insights from these approaches are included into the conception of the simulation model which will be implemented during this research initiative.

The application of multi-agent systems in economic research has lead to the novel and promising discipline of Agent-based Computational Economics (ACE). Within this discipline, a bottom-up approach to simulation economic markets is chosen. In contrast to the models of conventional simulation (e.g. system dynamics), in which participants are modeled in an aggregated way (top-down), participants are treated individually. This procedure enables a more realistic simulation.

By designing such a model a self evolving dynamic system is defined, which allows better insight into the processes and the results of strategic decisions in the power sector (Edmonds 2001; Tesfatsion 2003).

As shown in the mentioned work as well as within the development in different research areas in economics and computer science, the paradigm of multi-agent systems is very well suited for the design and the implementation of simulation systems. Especially deregulated power markets provide properties, which can be modeled using MAS in a neat way. Of course a set of assumption about the behavior of market participants has to be made. However, such a simulation system hast to be calibrated and validated using past data from reality. After this realistic setup of the system, future decisions can be simulated and their market outcome can be compared. These results can be used as acting recommendations for strategic decisions of certain participants as well as political decision makers.

2.3 Modeling of Fluctuating Energy Sources

We will model fluctuating renewable energy sources using suitable stochastic processes. Methods applied stem from the domains of statistics, signal processing and time series analysis.

Using recorded weather data (wind velocity, radiation data), time series of the electrical power generation are simulated by means of known plant characteristics and subsequently aggregated to load curves in typical production regions based on geographical plant distribution. The multivariate data set thus generated can be studied using conventional statistical methods. These include among others the analysis of average values, variance, probability distributions, linear and cross correlations as well as of power spectra.

Analyzing the predictability of these data using data-driven models has particular significance since this determines how the rest of the power generation system is able to cope with fluctuations. In order to determine the predictability, different models such as multivariate autoregressive models, neural networks, phase space methods are adapted to the data and their predictive accuracy is determined. From this examination, the fluctuations observed can be divided into deterministic and stochastic ones. Furthermore, the proportion of non-linear fluctuations in the data can be ascertained.

3 The Principle Design of the Market Simulation Model

Alongside energy-supply side participants such as public utilities, operators of plants using renewable energies and energy traders, the aim is also to model households and small commercial users as well as industrial companies via demand-side agents. Furthermore, regulatory authorities can be incorporated into the model as neutral agents. In the following more details are given based on the example of the different software agents who represent the various planning departments of an electric power company.

The investment planner in the electric power company, who is modelled as an autonomous software agent, analyses the expansion decisions of his company for a longer-term period (e.g. 20 years). To do so he refers, on the one hand, to exogenously given factors such as the current legal requirements and information about the already existing capacities of competitors. On top of this, market parameters are also entered into the decision process, such as the current electricity price, available to the investment planner as endogenous factors and the result of previous activity rounds.

Based on this information, forecasts are drawn up by the investment planner for the primary energy prices, the energy demand and finally the electricity prices which are necessary for planning expansion decisions. The (de)investments in power stations suggested by the investment planner are passed on to management and are evaluated by them based on the strategy they have selected. The information presented is weighted in such a way as to take the risk behaviour portrayed into account.

The short-term planner’s job is offer amounts of electricity on the electricity market. To do so he makes decisions using the management's strategy about how much electricity he should offer at which price at any one time on the market as well as under which conditions bilateral electricity contracts should be offered. Considering the hourly demand the market clearing will be achieved by the proper dispatching of the available power plants. The software agent can learn from his previous behaviour, i.e. he analyses which price/quantity strategies achieved the best results in past periods and then develops new trading strategies from these.

After these short-term market activities have been simulated for several months or after the frame conditions have changed, the investment planner gets actively involved again. The short-term planner and market intermediary provide the investment planner with information who then conducts his investment planning using this information and finally transmits the results of his plans to the management.

4 Expected Results

This new research approach of energy system modelling should result in fundamental insights into understanding market dynamics in the electricity sector after the introduction of CO_2-certificate trading and the increased use of renewable energies. In particular, the results can make an essential contribution to understanding the future development of air pollutants and greenhouse gases. Where today there is still a wall between energy models and policy-oriented analyses and ex-ante evaluations, this methodological approach ultimately offers the possibility of consistently and transparently simulating group-specific behavioural patterns and obstacles with energy policy measures.

Previous modelling concepts used to analyse electricity markets usually stem from the domain of operations research (OR). However, these modelling concepts have natural limits and the following shortcomings:

- Participant specific market strategies which go beyond simply maximising profits are not realisable or only to a limited extent.
- The interaction between electricity and certificate market is not or only insufficiently taken into account.
- Adaptations of the participants' strategies due to experience gained from success or failure on the market are not integrated.
- The interaction between strategic planning and the more short-term quantity-price strategies on the electricity market is not considered.
- The influence of expanding renewable energy sources on participant specific investment decisions is not sufficiently considered.
- Price formation based on marginal costs is frequently used which negates that profits are achievable by forming prices above marginal costs in certain market constellations or in certain market segments (such as households).
- The dynamics of the market due to the multitude of existing and new participants with their different functions is not depicted.
- The limited access of the participants to information is not considered.

Fundamental insights with reference to the current state of research are expected in the following areas:

- A more realistic picture of the structure of the electricity system in Germany for a planning horizon of 20 – 30 years depending on the prices for CO_2-certificate.
- Evaluation of CO_2 abatement possibilities among the various participants of the European Electricity Market.
- Development of regional pollutant emissions.
- The balancing power required for the inclusion of fluctuating energy forms.
- Forecasting the development of the energy demand.
- Composition of electricity production (share of nuclear, lignite etc.).

To summarize, it is expected that, based on flexible and agent-based simulation systems, a new method of simulation for the electricity market can be developed. Under application of this novel method it is expected that it will be possible to study the impacts of emission trading and increased usage of renewable energies on the market.

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