Assessment of the impact of renewable electricity generation on the German electricity sector
An agent-based simulation approach

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Preface

The issues of climate policy and security of supply are the main driving factors in the current debate on the electricity sector in Germany and throughout Europe. An important aspect of this debate is the growing awareness of the scarcity of natural resources. Renewable energy sources thus represent important pillars for the long-term development of the electricity sector in the given context. This thesis analyses the impact of the German support scheme for renewable electricity generation on the German electricity sector. It is the result of my research carried out at the Fraunhofer Institute for Systems and Innovation Research (FhG ISI) in Karlruhe.

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For my parents and my sister Corinna

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Abbreviations

ABS .... Agent-based simulation
AGC .... Automatic generation control
CC .... Combined cycle power plant
CDM........................ Clean development mechanism
CER .... Certified emission reductions
CGE......................... Computable general equilibrium
CHP .... Combined heat and power
CO_2.......................... Carbon dioxide
DB .... Database
DC .... Direct current
DM .... Deutsche Mark
ECX......................... European Climate Exchange
EEX .... European Energy Exchange
ERU......................... Emission reduction unit
EU .... European Union
EUA .... European emission allowances
GB .... Gigabyte
GHz .... Gigaherz
GT .... Gas turbine
GUI.......................... Graphical user interface
GW .... Gigawatt
HC .... Hard coal
HH........................... Households
I/O .... Input/output
ISI............................ Fraunhofer Institute for Systems and Innovation Research
JI.............................. Joint implementation
kg............................. Kilogramm
km .... Kilometer
kW .... Kilowatt
LG .... Lignite
LMP .... Locational marginal price
MB .... Megabyte
Mt .... Megaton
MW .... Megawatt
NAP......................... National allocation plan
OM .... Operation and maintenance
OTC......................... Over the counter
PC............................ Personal computer

PV ....Photovoltaic
RAM ....Random access memory
RES ....Renewable energy source
RES-E ....Electricity generation by renewable energy sources
RMSE ....Root mean squared error
SD ....System dynamics
SSH ....Secure shell
t ....Ton
TWh ....Terawatt
UCTE.......................Union for the Co-ordination of Transmission of Electricity
UK ....United Kingdom
USA ....United States of America
VV ....Negotiated Third Party Agreement
WD...........................Weekday
WE ....Weekend
WPMP......................Wholesale Power Market Platform
XML ....Extensible Markup Language

1 Introduction

1.1 Background

The issues of climate policy and security of supply are the main driving factors in the current debate on the electricity sector in Germany and throughout Europe. An important aspect of this debate is the growing awareness of the scarcity of natural resources. Both issues interact as those energy sources with the lowest carbon content such as gas and oil also have the shortest range concerning current consumption and known reserves. Those resources with the highest carbon content such as lignite and hard coal are characterized by longer ranges and a more even distribution around the world (Bundesanstalt für Geowissenschaften und Rohstoffe [BGR], 2007). Renewable energy sources thus represent important pillars for the long-term development of the electricity sector in the given context. Renewable energy sources rely on the energy that is provided by thermal processes within our planet and solar radiation which is inexhaustible in human terms. Since renewable energy sources are also characterized by low CO_2 emissions which are mainly caused by the manufacturing process (Marheinke et al., 2000), they can help to overcome the described dilemma of scarce resources and climate protection.

The strategy to increase the share of renewable energy sources in electricity generation has also found its way into policy making on a national and a European level. At a European level, the RES-E Directive (Commission of the European Communities, 2001) has set the target to increase the share of renewable energy sources to 12 % of gross domestic energy consumption. The target for the electricity sector is set at a share of 22 % of the gross electricity consumption in the European Union (EU-15) until 2010. The recent decision of the European Commission to increase the share of renewable energies in total energy consumption to 20 % necessitates an ambitious growth of renewable energies throughout the entire energy sector including the electricity sector (Commission of the European Communities, 2007). In Germany the government began stimulating the market penetration of renewable electricity generation in the 1990s. After a period of support consisting mainly of research and development programmes, fixed feed-in tariffs were introduced in 1990. Despite several modifications, the principal system of feed-in tariffs has been in place for more than 15 years in Germany. In combination with additional support schemes such as soft loans with reduced interest rates, the German support policy has led to a remarkable growth in renewable electricity generation. In 1990, most of the renewable electricity generation was based on large hydropower plants. The electricity generation by other technologies such as wind, photovoltaics and biomass was less than 0.3 TWh. (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2006b). As a consequence of the continuous support, electricity generation from new renewable energy sources reached more than 52 TWh in 2006 (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2007a). The most important technology within this development is electricity generation from wind energy which attained an exponential growth from an installed capacity of 56 MW in 1990 to 20622 MW (Deutsches Windenergie Institut [DEWI], 2007) by the end of 2006. The considerable capacity and the fluctuating character of electricity generation by wind have triggered a debate on the effect of wind power on the electricity sector.

Another aspect which has to be taken into account is the change in the framework conditions of the German and the European electricity sector. The process of liberalization has changed the structure of players within the sector. Several markets for electricity and balancing reserve have been established. These markets play an increasing role for investment decisions and the operation of power plants. A second important change is the increasing importance of climate policy and the introduction of the European Emissions Trading System which creates market prices for CO_2 emission allowances.

In the given context of interacting markets the supported renewable electricity generation has a number of impacts on the electricity sector and its players. These impacts are not only limited to technical issues such as grid extension and balancing of the system. Due to the considerable volume of the renewable electricity generation, the support payments have reached a total of more than 5 billion Euro (Verband der Netzbetreiber [VDN], 2007b). Other important aspects are the influence on the CO_2 market and the market prices on the wholesale market for electricity. These effects lead to considerable monetary flows within the sector.

1.2 Problem definition

The defined targets for renewable electricity generation on national and European level show that the importance of renewable electricity generation is likely to increase strongly. In line with the political debate on the targets for renewable electricity generation, an intensive debate is taking place on the different support schemes for renewable electricity generation. Therefore it seems essential to obtain a clearer picture of the interactions of supported renewable electricity generation and the electricity sector. The analysis of the various impacts and monetary flows is an important issue in order to better understand the effects of supported renewable electricity generation. The effects of renewable electricity generation on electricity market prices play an important role here as changes in market prices affect all the players in the electricity sector. Thereby it is important to take the characteristics of the electricity market into account. Especially the shape of the supply curve plays an important role. While base load power plants, such as nuclear fired power plants, have variable electricity generation cost of ca 11 Euro/MWh peak load power plants can have generation cost of ca. 90 Euro/MWh. The supported renewable electricity generation reduces the demand that has to be covered by conventional power plants. As a result the most expensive plants are no longer needed to cover the demand in a given hour. Due to the shape of the supply curve this effect can have a considerable impact on market prices. Furthermore the considerable financial volume of the wholesale market for electricity has to be taken into account. If the entire net electricity production of 559 TWh (Union for the Co-ordination of Transmission of Electricity [UCTE], 2007), is multiplied by the average market price of the German spot market EEX in 2006 of 50.8 Euro/MWh (European Energy Exchange [EEX], 2007e) the value of the generated electricity can be estimated to 28 billion Euro. Considering these framework conditions even small amounts of supported renewable electricity generation can create effects of considerable financial volume. Due to the interactions of renewable electricity generation with the electricity sector it seems important to discuss the effects not only in a qualitative way, but also to provide quantification in monetary terms in order to assess their importance. This assessment could help scientists and policy makers to identify and pay more attention to the most important issues. Using a computer model for such an assessment seems inevitable taking into account the complexity of the interactions and the enormous amount of data necessary for the analysis. In the given context it has to be stated that the analysis carried out in this thesis does not deal with the issue of external costs related to electricity generation by different enery sources such as fossil fuels and renewable energy sources. A discussion of this issue can be found in the literature (Schlomann and Krewitt, 2006; Hohmeyer, 2002).

The applied modelling approach has to fulfil several requirements. On the one hand the model has to deal with a considerable amount of data on power plants and renewable electricity generation. Since market prices on the spot market for electricity vary by the hour, the model has to be capable of dealing with this timescale. On the other hand the model also has to reflect the current situation on the electricity market which has evolved from centralized planning within a given supply region to the market-orientated interaction of several players.

1.3 Objective and procedure

The central goal of this thesis is to analyse and quantify the major impacts of renewable electricity generation on the electricity sector. Special emphasis is given to the interaction on the markets of the electricity sector and the resulting impacts on different players. The task poses new challenges to the computational analysis of the electricity sector. In order to deal with this, a simulation platform is developed which is based on the concept of agent-based simulation. The main challenge involved is the level of detail applied and its consequences for the resulting requirements concerning the management of data and computational resources. Therefore the model development itself becomes a further objective of this thesis.

In order to provide a basis for the further analysis, Chapter 2 reviews major developments within the German electricity sector over the past two decades which are relevant for this thesis. Special attention is paid to the renewable support scheme.

Based on the analysis of the German electricity sector, the criteria for a suitable modelling approach are developed in Chapter 3. Existing modelling approaches are discussed and evaluated based on the developed criteria. The most promising modelling approach is then selected.

Chapter 4 analyses the current scientific status of the selected approach of agent-based simulation of the electricity sector. The major developments of various groups of scientists are examined and the major streams of ongoing research are highlighted. The central goal is to determine the current status of the selected new modelling approach in order to provide a background for the own model development.

Chapter 5 describes the developed simulation platform with regard to the applied algorithms and data. Based on a detailed representation of load, renewable electricity generation and the German power plant portfolio, the model can be used to simulate several interacting electricity markets such as the spot market and the balancing market. The model results are compared to real world market prices in a calibration procedure.

In Chapter 6 the developed simulation platform and the available data in the literature are used to analyse the impact of renewable electricity generation on the German electricity sector. Special emphasis is given to the interaction of supported renewable electricity generation and the electricity market.

In Chapter 7 three additional applications of the developed agent-based simulation platform are described in order to demonstrate the flexibility and capability of the applied modelling approach. The examples described show possibilities for future research and for the future extension of the developed simulation platform.

The last chapter, Chapter 8, provides a summary of the thesis, conclusions and an outlook.

2 Relevant developments in the German electricity sector

The German electricity sector has experienced considerable changes throughout the past 15 years. Major developments are the liberalization of electricity markets and the emergence of climate policy which led to the German support for combined heat and power plants [CHP] and the introduction of the European emission trading system. Other important aspects are the beginning phase out of nuclear energy and the support for renewable electricity generation leading to a considerable growth in renewable electricity generation. The goal of this chapter is to provide an overview of these main developments and their major consequences in order to provide a background for the analysis carried out in this thesis.

2.1 Liberalization of electricity markets

Over a period of decades the German electricity sector has been characterized by regional monopolies. The operation of the low voltage grid and the supply of end consumers were carried out by ca. 800 local municipal utilities owning only minor parts of the generation capacity. The high voltage grid was operated by regional utilities. The transmission grid and most of the generation capacity was owned and operated by eight interconnected utilities. Electricity companies supplied consumers of a given region without the interference of competitors (Fichtner, 2005). This structure has been changed by the liberalization of electricity markets. An overview of the main developments and its consequences is given in this section.

2.1.1 Development

In 1996 the European Union started the process of the liberalization of electricity markets with the electricity market directive (Commission of the European Communities, 1996). It required a stepwise opening of the market for competition (Commission of the European Communities, 1996, Art 19). A main requirement of the directive is separate book keeping for the generation and transmission departments of integrated utilities. The directive allowed countries to choose between negotiated and regulated grid access. Germany implemented the rules of the directive with an amendment of the "Energiewirtschaftsgesetz" (Bundesministerium für Wirtschaft und Technologie [BMWI], 1998). By opening the market for all consumers, the German government went beyond the requirements of the directive. However, in case of the grid access the government opted for the negotiated third party access which required new market players to negotiate contracts with the grid operators. Three major industrial organizations (VDEW, VIK, BDI) developed a common set of rules for the access to the electricity grid called Negotiated Third Party Agreement (Verbändevereinbarung). According to the rules of the first Negotiated Third Party Agreement the tariffs for grid access were dependent on the distance of the entry and exit point (Bundesverband der Deutschen Industrie et al., 1998). However, the rules proved to be too complicated thus hindering market opening. Therefore the Negotiated Third Party Agreement was revised in 1999 (Bundesverband der Deutschen Industrie et al., 1999). The revised version (VV II) replaced the distance dependent tariffs by a single tariff. Another improvement was the introduction of synthetic load profiles which reduces the metering requirements for small consumers changing their suppliers (Bundesverband der Deutschen Industrie et al., 1999, 4.1). The transmission grid was divided into a northern zone and a southern zone. An additional charge of 0.125 cent/kWh was introduced for trades across this virtual border. Another revision of the Negotiated Third Party Agreement took place in 2001 (Bundesverband der Deutschen Industrie et al., 2001). It was mainly the result of two mergers between RWE/VEW and Preussen Elektra and Bayernwerk forming the two biggest utilities (RWE and EON) in Germany. The German competition authority (Bundeskartellamt) allowed the mergers on special conditions. Among these was the abolishment of the additional charge for electricity trades between the northern and southern zone. Despite the complete market opening in 1998 the actual market opening took more than three years. In 2001 80 % of the consumers could effectively choose their suppliers (Promit and Verband der Elektrizitätswirtschaft, 2002). In 2003 the "Energiewirtschaftsgesetz" was revised. It mainly affected the liberalization of gas markets but it also acknowledged the Negotiated Third Party Agreements as "best practice" (Bundesministerium für Wirtschaft und Technologie [BMWI], 2003, §6 3-4).

In 2003 the EU passed the new directive 2003/54/EC in order to speed up the development of a liberalized electricity market. The central aspect is that the directive requires the member states to regulate the access to the electricity grid. The member states are required to establish regulatory authorities (Commission of the European Communities, 2003a, §3). The regulatory authorities have to determine the rules for the calculation of "grid fees" and the procurement of reserve energy. Another important aspect is that the directive requires a stronger separation of network operators for both transmission and distribution networks in case of integrated utilities. Although the ownership remains unchanged, the network operators have to be legally separated. Since the German system of negotiated third party access was no longer in accordance with the EU directive, the German "Energiewirtschaftsgesetz" had to be adjusted until July 2004. In July 2005 the German government implemented the EU directive in a new "Energiewirtschaftsgesetz" (Bundesministerium für Wirtschaft und Technologie [BMWI], 2005). The new regulatory authority "Bundesnetzagentur" was created whose main task is the regulation and approval of grid-fees (Bundesministerium für Wirtschaft und Technologie [BMWI], 2005, §21,§21a,§23). It is also entitled to determine the rules for the purchase of system-services. The new law also implemented the requirement of the directive that consumers have to be informed about the energy sources and the environmental indicators like CO_2 emission and nuclear waste connected with bought electricity (Bundesministerium für Wirtschaft und Technologie [BMWI], 2005, §42). In general the development shows that there is a tendency towards stronger regulation of the liberalized markets.

2.1.2 Consequences

In line with the liberalization of the electricity sector new markets evolved. In June 2000 the first German day-ahead spot market for electricity Leipzig Power Exchange started operation (European Energy Exchange [EEX], 2000). Two months later a second competing spot market (European Energy Exchange) went into operation (Tagesspiegel, 2000). After a short period of competition both spot markets merged under the name of the European Energy Exchange [EEX] (European Energy Exchange [EEX], 2002). A further development of the market place was the introduction of an intra day market in 2006 (European Energy Exchange [EEX], 2006). Throughout the same period the markets for the procurement of reserve energy evolved. After a period of procurement on the level of transmission zones, the rules of the procurement of reserve capacity are now subject to regulation (also see Bundesnetzagentur, 2006).

The liberalization of the electricity market has changed the sector dramatically. During the period of regional monopolies the task of utilities was to ensure system stability by covering their load profile at reasonable cost (Fichtner, 2005). In a liberalized electricity market generation capacities compete according to their cost. Apart from restrictions concerning the national and European electricity grid competition takes place on national or European level. Profits for generators are no longer fixed. However, generation capacity in the German electricity sector is characterized by strong concentration. As the result of the mergers in the period 2000-2002 the four biggest utilities Eon, RWE, Vattenfall Europe and EnbW own 90 % of the German generation capacity (Brunekreeft and Bauknecht, 2006, p.239).

The consumer market has been characterized by different developments. During the first period (1998-2000) prices fell especially for industrial consumers but also in the household sector. After the year 2002 prices started to rise again (Bundesministerium für Wirtschaft und Technologie [BMWI], 2006). This development cannot solely be ascribed to the amount of competition within the market. Rising fuel prices may also have contributed to this development.

2.2 CO_2 emission trading

Economic growth and industrialisation have led to a strong growth in energy consumption through the past 150 years. Since energy supply is heavily based on fossil fuels like coal, oil and gas, the worldwide CO_2 emissions have grown considerably. The result is a rise in the CO_2 concentration in the atmosphere. During the end of the 20th century and the beginning of the 21st century scientific studies accumulated increasing evidence that the increasing concentration of greenhouse gases (especially CO_2) in the atmosphere is likely to cause global warming (Intergovernmental Panel on Climate Change, 2007). This process of global warming could lead to considerable changes in the world climate like the melting of the polar ice caps, a rise of the sea level and an increase of extreme weather conditions. These developments can have considerable impact on human societies, especially in the least protected poor regions of the world. In 1992 the United Nations Framework Convention on climate change (Rio de Janeiro) acknowledged the danger that is caused by the man made increase of greenhouse gases in the atmosphere (United Nations, 1992, §2). The goal of the convention is to stabilize green house gas concentration in the atmosphere (United Nations, 1992, §2). In 1997 the Kyoto Protocol determined individual targets of greenhouse gas emissions for a group of mostly industrialized countries (United Nations, 1998).

2.2.1 Development

The European Union committed itself to reduce its greenhouse gas emission by 8 % until 2012 compared to the base year period. The EU reduction target is broken down to reduction targets for single countries. These targets are very different. While further growth is allowed for the southern European states northern countries like Germany and Denmark have to reduce their emissions by 21 %. However, the development in the period 1990-2000 shows that many EU countries are far from fulfilling their reduction targets. An overview of the reduction targets and the development in the period 1990-2000 is given in Table 2-1.

As a consequence of the low target fulfilment within the EU the European Commission developed a concept for a European emission trading system (Commission of the European Communities, 2000, p.6). In 2002 the ministers for environment agreed on the basic concept for a European emission trading system (Fichtner, 2005, p.16). The development resulted in the EU directive 2003/87/EC on a European emission trading system (Commission of the European Communities, 2003b). The first trading period is the period 2005-2007. The second period concerns the years 2008-2012. The directive requires the member states to allocate at least 95 % of the permission free of charge. In the second period this value is reduced to 90 % (Commission of the European Communities, 2003b, Art. 10). The European emission trading system is a trading system between companies (Fichtner, 2005, p.17). The national governments have to develop national allocation plans. These plans have to be accepted by the European Commission in advance (Commission of the European Communities, 2003b, Art.9).

Table 2-1: Greenhouse gas emissions in the EU

Member State	**Base year**	**2002**	**Change 2001 – 2002**	**Change Base year – 2002**	**Targets 2008 – 2012**
	Mt	**Mt**	**%**	**%**	**%**
Austria	78.0	84.6	0.3	8.5	-13.0
Belgium	146.8	150.0	0.5	2.1	-7.5
Denmark	69.0	68.5	-1.2	-0.8	-21.0
Finland	76.8	82.0	1.7	6.8	0.0
France	564.7	553.9	-1.4	-1.9	0.0
Germany	1,253.3	1,016.0	-1.1	-18.9	-21.0
Greece	107.0	135.4	0.3	26.5	25.0
Ireland	53.4	68.9	-1.6	28.9	13.0
Italy	508.0	553.8	-0.1	9.0	-6.5
Luxembourg	12.7	10.8	10.4	-15.1	-28.0
Netherlands	212.5	213.8	-1.1	0.6	-6.0
Portugal	57.9	81.6	4.1	41.0	27.0
Spain	286.8	399.7	4.2	39.4	15.0
Sweden	72.3	69.6	2.0	-3.7	4.0
United Kingdom	746.0	634.8	-3.3	-14.9	-12.5
EU 15	**4,245.2**	**4,123.3**	**-0.5**	**-2.9**	**-8.0**

Source: European Environment Agency, 2004, p.11

Companies owning installations which have to take part in the emission trading system have to provide allowances for their annual emissions until the end of April of the following year (Commission of the European Communities, 2003b, Art.16). The penalty for emissions which are not covered by permits is set to 40 Euro/t in the first period and 100 Euro/t in the second period (Commission of the European Communities, 2003b, Art.16). The penalties have the effect of a price cap on the market. Germany provided the legal framework for the emission trading with the implementation of the "Treibhausgasemissionshandelsgesetz" in 2004. In case of electricity production, heat or steam production all plants with a thermal capacity of

20 MW have to take part in the emission trading system. Big production units of other sectors like iron and steel, cement or oil industry are also included in the emission trading system. The specifications of production units to be included in the emission trading system are given in the Appendix of the law (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2004b). In total 2400 units have to take part in the German emission trading system (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2007c). The amount of CO_2 permissions allocated for the first trading period 2005-2007 is 2 Mt lower than in the emissions of the reference period 2000-2002. The emission budgets and the accounts of participants are administered by a new authority "German Emissions Trading Authority" [DEHSt] within the Federal Environmental Authority [UBA]. The current allocation plan of November 2006 proposes a reduction of annual CO_2 emissions by 34 Mt to 465 Mt in the second period (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2006a).

After the start of the emission trading system several trading places evolved. The German EEX started a spot market for CO_2 in March 2005 (European Energy Exchange [EEX], 2005b). The introduction of a future market followed in October 2005 (European Energy Exchange [EEX], 2005a). Other important trading places in Europe are the European Climate Exchange (ECX), Nordpool and PowerNext.

In addition to emission reductions within a country the Kyoto Protocol allows to take credit for emission reductions in foreign countries via the flexible mechanisms. The clean development mechanism [CDM] (United Nations, 1998, Art. 12) allows the mostly industrialized Annex I countries to carry out greenhouse gas reduction programmes in developing countries. The generated savings can used to fulfil the own reduction targets. The implementation of CDM projects can be used to generate certified emission reductions [CER].

Another flexible mechanism of the Kyoto Protocol is joint implementation [JI] (United Nations, 1998, Art.6). Joint implementation allows to carry out joint projects within Annex I countries and to take credit for the created greenhouse gas reductions. The accounting for emission reductions of joint implementation projects takes place in terms of emission reduction units [ERU].

The integration of flexible mechanisms into the European emission trading system is defined by the Linking Directive of 2004 (Commission of the European Communities, 2004). The approval and accounting for flexible mechanisms is carried out by national authorities. In the first period (2005-2008) only CER generated by CDM projects can be converted into European emission allowances [EUAs]. In the second period (2008-2012) ERU created via joint implementation can be converted, too. The Linking Directive was implemented in German law by the Project Mechanisms Act of 2005 (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2005a). A central requirement for the approval of projects is additionality. The project has to create greenhouse gas reductions compared to the baseline development (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2005a, §3). Another important requirement is that the project causes no severe damages to the environment. Large hydro power plants with a capacity higher than 20 MW must adhere to additional criteria (§3). Nuclear projects cannot be approved within the flexible mechanisms (Commission of the European Communities, 2004, §11a).

2.2.2 Consequences

The electricity sector has the highest CO_2 emissions within the German allocation plan. In the period 2000-2002 power plants produced 316 Mt CO_2 emissions per year (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2004c, p.15). Due to its size the electricity sector has an important impact on the development of CO_2 prices, but it is also affected by the development of CO_2 prices. Abstracting from some complex allocation rules, CO_2 permits are a new production factor of power plants which has to be taken into account. Power plants consume CO_2 emission permits [EUA] by emitting CO_2. Since the markets determine a price for CO_2 emissions, this price has to be considered in planning and pricing processes of the sector. In the short run the CO_2 price affects the variable cost of a power plant and in consequence its position in the markets. Plants with high specific CO_2 emission like lignite power plants are more affected than power plants with lower CO_2 intensity like gas fired power plants. In the long run the emission trading also affects investment decisions for power plants. Investors have to consider the allocation rules and the expected future CO_2 prices in order to determine the profitability of investment decisions.

2.3 Support for combined heat and power plants

During the first year of the liberalized electricity markets prices fell and the electricity companies started to reduce their cost. In the given situation many combined heat and power [CHP] plants were no longer profitable. As consequence the electricity companies started to shut down combined heat and power [CHP] plants, which led to a significant reduction of the installed capacity (Arbeitsgemeinschaft Fernwärme e.V.[AGFW], 2000 p. 561). Since CHP plants use fuel more efficiently than conventional plants, they help to reduce CO_2 emissions (Lutsch and Witterhold, 2005, p. 21ff.). Therefore the shut-down of CHP plants endangered the goal of the German government to reduce CO_2 emissions. This development led to the pressure to establish a support scheme for CHP plants. The developed scheme and its main consequences are described in this section.

2.3.1 Development

In 2002 the German government passed a law for the support of CHP plants. The law was part of the climate strategy of the German government published in 2000 (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2000b, p.10). By preservation, modernization and extension of CHP plants CO_2 savings should be created. The stated goal is to reduce the annual CO_2 emissions to the base year 1998 by 10 million t in 2005 and a minimum of 20 million t in 2020 (Bundesministerium für Wirtschaft und Technologie [BMWI] and Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2002, §1). Grid operators are obliged to buy electricity generated by CHP plants. The minimum payment is the average base load price on the European Energy Exchange (Bundesministerium für Wirtschaft und Technologie [BMWI], Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2002, §4). An additional premium has to be paid by the grid operators. The value of the premium depends on the age and technology of the plant and the year. An overview is given in Table 2-2. After a balancing process between the grid operators the cost of the support can be integrated into the calculation of the grid charges. The validity of the law and its support scheme are limited to the end of 2010.

Table 2-2: Overview of CHP premiums

Plant category		Premium in cent/kWh	Duration of payment
Existing plants	Existing plants	1.53	2002 – 2003
		1.38	2004 – 2005
		0.97	2006
	New plants	1.53	2002 – 2003
		1.38	2004 – 2005
		1.23	2006 – 2007
		0.82	2008
		0.56	2009
	Modernized plants	1.74	2002 – 2004
		1.69	2005 – 2006
		1.64	2007 – 2008
		1.59	2009 – 2010
New plants	Small plants (up to $2MW_{el}$)	2.56	2002 – 2003
		2.40	2004 – 2005
		2.25	2006 – 2007
		2.10	2008 – 2009
		1.94	2010
	Small plants (up to 50kWel) Fuel Cells	5.11	10 years

Source: Based on Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2007b

2.3.2 Consequences

The support scheme for combined heat and power plants increased the electricity production by CHP plants. The electricity production of plants affected by the support rose from 31.6 TWh in 2002 to 52.2 TWh in 2004 (Blesl et al., 2005, p.34). In terms of electricity generation the law affects less than 10 % of the net electricity production, but in terms of the installed peak capacity of supported power plants it reaches a value of ca. 38 GWel. A recent evaluation of the support scheme for CHP plants shows that it stimulated the modernization and construction of CHP plants (Blesl et al., 2005, p.42). However, the evaluation also shows that the goals in terms of CO_2 savings for the year 2005 are only reached in the optimistic estimation. The target of 20 Mt CO_2 savings for the year 2010 is not likely to be reached in the current projection (Bundesministerium für Wirtschaft und Technologie [BMWI] and Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2006b).

The main impact on the entire electricity sector is that the electricity generation by CHP plants has a privileged access to the electricity grid. Similar to renewable electricity generation, the electricity has to be bought by grid operators thereby reducing the size of the market for all other technologies.

2.4 Nuclear phase out

Electricity generation by nuclear power plants plays an important role in the German electricity sector. The explosion of the nuclear power plant in Tschernobyl in 1986 raised a considerable debate on the future of nuclear power plants in Germany. The debate was also fired by the unresolved issue of nuclear waste disposal. In the nineties environmentalists fought against the transport of nuclear waste to the planned terminal storage in Gorleben. In 1998 the German government changed. The new coalition of social democrats and the green party decided the phase out of nuclear energy in Germany. This section describes the main facts of the nuclear phase out in Germany and its consequences for the electricity sector.

2.4.1 Development

After negotiations the electricity industry and the German government signed an agreement on the phase out of nuclear energy in Germany (Bundesregierung, 2000). The agreement was framed by a law in 2002 (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2002). It forbids the construction of new commercial nuclear power plants in Germany. Existing plants are allowed to produce a certain amount of electricity which is equivalent to full utilization for 32 years. The utilities are allowed to transfer these electricity budgets from older plants to other nuclear plants. An exception is the plant in Mülheim Kärlich which lost its operation permission shortly after construction. The owners of this plant can transfer its electricity budget to other nuclear plants. An overview of the German nuclear power plants and their electricity budget is given in Table 2-3.

Table 2-3: Overview of German nuclear power plants

	Electricity budget* TWh	**Gross capacity** MW	**Begin of operation** year	**Status**
Obrigheim	8.7	357	1969	closed 2005
Stade	23.18	672	1972	closed 2003
Biblis A	62	1,225	1975	in operation
Neckarwestheim	57.35	840	1976	in operation
Biblis B	81.46	1,300	1977	in operation
Brunsbüttel	47.67	806	1977	in operation
Isar	78.35	912	1979	in operation
Unterweser	117.98	1,425	1979	in operation
Philippsburg 1	87.14	926	1980	in operation
Grafenrheinfeld	150.03	1,345	1982	in operation
Krümmel	158.22	1,376	1984	in operation
Grundremmingen	160.92	1,344	1984	in operation
Philippsburg 2	198.61	1,458	1985	in operation
Grohnde 1	200.9	1,430	1985	in operation
Grundremmingen C	168.35	1,344	1985	in operation
Brokdorf	217.88	1,440	1986	in operation
Isar 2	231.21	1,475	1988	in operation
Emsland	230.07	1,400	1988	in operation
Neckarwestheim 2	236.04	1,395	1988	in operation
Mülheim-Kärlich	107.25	1,302	1986	closed 1988
* According to Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2002, Status 2000				

Sources: Bundesamt für Strahlenschutz, 2007

2.4.2 Consequences

So far two nuclear power plants have been shut down after the decision on the nuclear phase out in Germany. The plants in Stade and Obrigheim went out of operation in 2003 (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2005b) and 2005 (E.ON, 2003). But nuclear electricity generation still plays an important role. In 2005 Germany produced ca. 28 % of its electricity by nuclear power plants (based on: Union for the Co-ordination of Transmission of Electricity [UCTE], 2007, Bundesministerium für Wirtschaft und Technologie [BMWI] and Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2006a). In total 17 plants with an installed gross capacity of 21.4 GW produced 154.6 TWh of electricity thus forming an important part of the German electricity sector. Within the next two decades the phase out of the nuclear power plants, which are mainly used in the base load, requires the construction of a considerable amount of new power plants in replacement of the nuclear plants. This development increases the importance of other generation technologies like fossil fired thermal plants and renewable energies. Since this development is also likely to influence the CO_2 emissions and the dispatch of the power plant portfolio, it has to be taken into account for the analysis of the impact of renewable electricity generation on the electricity sector.

2.5 Support for Renewables

An important aspect for the development of the electricity sector in Germany is the growing role of electricity generation by renewable energy sources. The increasing importance of renewable electricity generation is the result of an effective support policy by the German government. After a long period of support in terms of research and development programmes the government started a direct support of renewables with the "100 MW wind programme" in 1989 which provided capital grants for investments into wind power plants. In the following years a number of additional support policies were added.

The core of the German support scheme is a guaranteed feed-in tariff system which started in 1991 with the introduction of the "Electricity Feed-In Law" in 1990 (Bundesministerium für Wirtschaft und Technologie [BMWI], 1990). This law required public utilities to buy electricity generated by renewable technologies at a fixed percentage of the retail price of electricity. In the year 2000 the "Electricity Feed-Law" was succeeded by the Renewable Energy Act. The Renewable Energy Act required public utilities to buy electricity generated by renewables at a given price. Minor revisions of the given law took place in 2004 and 2006. This development has led to an uninterrupted feed-in support for most renewable electricity generation technologies since 1990. On European level the goal to promote renewable energy gained legal importance with the directive 2001/77/EC (Commission of the European Communities, 2001). It sets the goal on European level to increase the share of renewable energy production to 22.1 % (EU 15) of the gross electricity consumption in 2010 (Commission of the European Communities, 2001(7)). Germany has to increase the share of renewable energy sources in the electricity sector to 12.5 % in 2010 (Commission of the European Communities, 2001, Annex).

In addition to the feed-in support several other support schemes stimulated the development of renewables in Germany. Among these are several programmes for the provision of soft loans with reduced interest rates or programmes providing capital grants. A prominent example is the ongoing Environment and Energy Saving Programme which started in 1990 and played an important role for the financing of wind energy projects. Other important examples are the "1000 Roof programme" and its successor, the "100.000 roofs programme" supporting the development of photovoltaics. Additionally a number of smaller support schemes existed on regional or community levels.

In the following section the most important renewable electricity generation technologies will be described with regard to their development and the main support schemes. Thereafter the main consequences and interactions with the electricity sector are discussed.

2.5.1 Wind energy

2.5.1.1 Development

The development of wind energy is the most remarkable example for renewable electricity generation technologies. Starting with an installed capacity of 18 MW in the year 1989, the continuous support has led to a considerable growth to 18,428 MW (Deutsches Windenergie Institut [DEWI], 2006) at the end of 2005. In 2005 4.3 % of the German electricity generation was generated by wind energy thus making wind energy the most important renewable electricity generation technology in Germany (based on (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2006c). An overview of the development of the installed capacity is given in Figure 2-1.

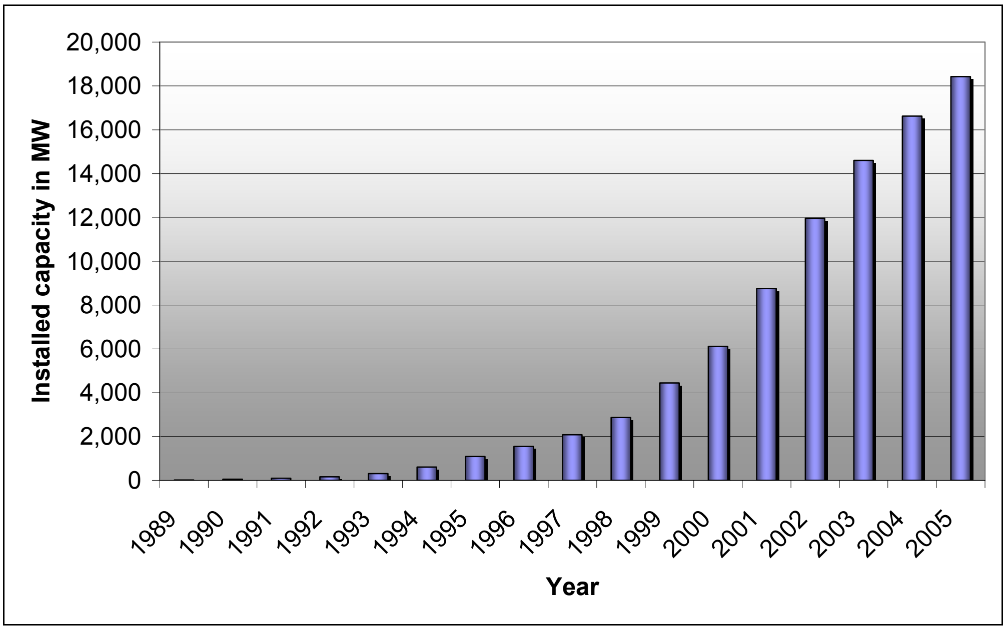

Figure 2-1: Development of wind energy in Germany

Sources: based on Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2006c, Institut für Solare Energieversorgungstechnik [ISET], 2006

2.5.1.2 Support

As presented in the previous section, the direct support for wind energy started with the launch of the 100 MW wind programme in 1989 issuing capital grants to investors. This programme was extended to a "250 MW wind programme" in 1991. Additional capital grant support was available by the 100 million DM programme between 1995-1998 (International Energy Agency [IEA], 2004, p.312). Another important contribution to the dynamic development was the provision of soft loans with reduced interest rates. Its importance can be seen by the fact that ca. 81 % of the investments in wind energy installations of the year 2003 were based on soft loans (Held, 2005, p.102). The most prominent example is the Environment and Energy Saving Programme which has been in force since 1990. The Electricity Feed-In Law obliged the grid operators to buy electricity generated by wind energy at a tariff of 90 % of the retail price (Bundesministerium für Wirtschaft und Technologie [BMWI], 1990, §3(1)).

The succeeding Renewable Energy Act introduced a high and a low tariff of 91 Euro/MWh and 61.9 Euro/ MWh (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2000a §7(1)). Since the length of the period where the high tariff is paid depends on the wind conditions of the site, this system introduces a slight diversification according to the profitability of the site. Another important aspect of the Renewable Energy Act is the introduction of an annual reduction of the tariff of 1.5 % per year after 2001 in order to induce cost reductions for the technology. In 2004 the Renewable Energy Act Amendment was passed which changed the tariffs to 87 Euro/MWh and 55 Euro/MWh and increased the annual reduction of the tariff to 2 % (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2004a). An overview of the development of the main support schemes for wind energy is given in Figure 2-2.

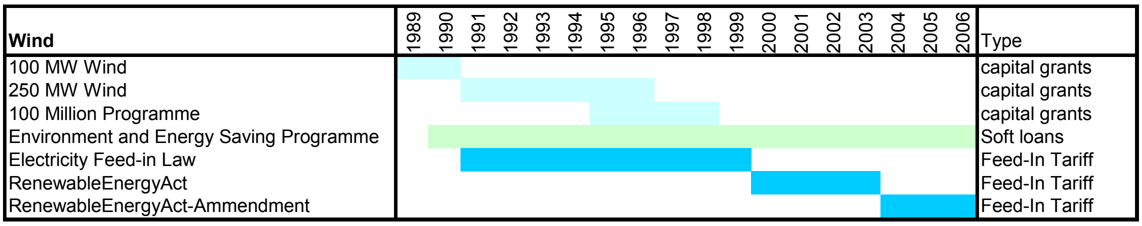

Figure 2-2: Main support schemes for wind energy in Germany

Source: own illustration

2.5.2 Photovoltaics

2.5.2.1 Development

The development of photvoltaics in Germany has mainly been driven on by the German support policy and the popularity of the technology. Starting with an installed capacity of 2 MW in 1991, the support led to a considerable growth to 1508 MW at the end of 2005. An overview of the development of the installed capacity is given in Figure 2-3.

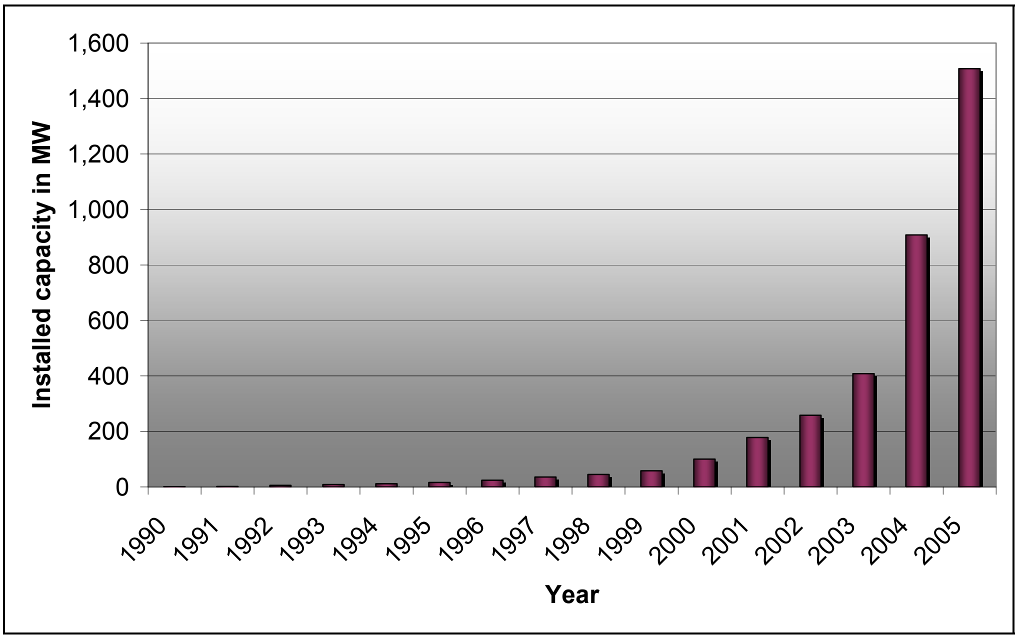

Figure 2-3: Development of photovoltaics in Germany

Source: Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2006c

2.5.2.2 Support

In 1991 the government initiated the 1000 roofs programme which provided capital grants for the installation of photovoltaic systems. Additional support was provided by the Electricity Feed-In Law providing a feed-in tariff of 90 % of the retail price (Bundesministerium für Wirtschaft und Technologie [BMWI], 1990, §3(2); Deutsches Windenergie Institut [DEWI], 2006). Additional capital grants were available by the 100 million DM programme from 1995 to 1998. However, the 1000 roofs programme ended in 1995 without succeeding support. It is remarkable that the installed capacity of PV continued to grow despite the reduced support and its comparatively high cost. This may be caused by the fact that PV is a very popular technology. It is probably the renewable technology which has the strongest perception of environmental friendliness in the public opinion. The development of the installed capacity accelerated considerably with the launch of the 100.000 roofs programme in 1998 providing soft loans and the Renewable Energy Act of 2000 which provided a heavily increased feed-in tariff of 50.62 Euro/MWh in succession of the Electricity Feed-In Law. Depending on the type and size of the installation, different tariffs are applied (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2000a, §8). Another important landmark in the German support for PV is the year 2004 where the 100.000 roofs programme ended. As compensation the feed-in tariff was raised to 57.4 Euro/MWh for small size installations below 30 kW installed capacity in the Renewable Energy Act Amendment. In the Amendment a differentiation of the tariff according to the size and type of the installation was introduced. In 2004 and 2005 the installed PV capacity almost doubled for two years in row. An overview of the development of the main support schemes for photovoltaics is given in Figure 2-4.

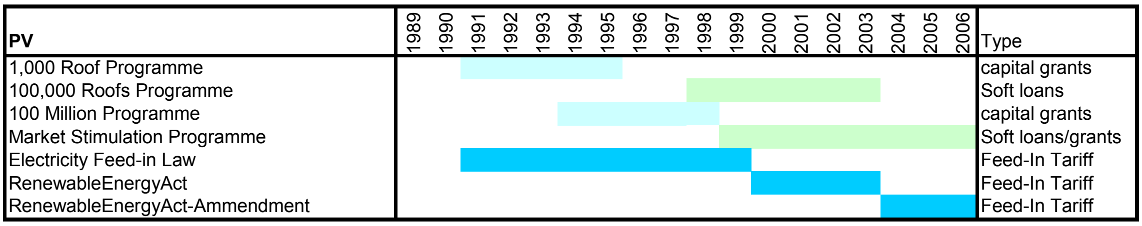

Figure 2-4: Main support schemes for photovoltaics in Germany

Source: own illustration

2.5.3 Biomass

2.5.3.1 Development

The category of renewable electricity generation based on biomass is an aggregate for various generation technologies. These include solid and gaseous technologies. Due to the German support scheme for renewable electricity generation the installed capacity for biomass technologies increased considerably from ca. 130 MW in 1992 to more than 2000 MW in 2005. Although growth took place for all technologies, the utilization of the existing potential is different. While the available potential for landfill gas and sewage gas can be considered to be almost completely developed, there is still some potential for solid biomass and biogas (based on: Hirschl et al., 2002, p.60). The later technologies showed the strongest growth throughout the past ten years. An overview of the development of the discussed technologies in terms of installed capacity is given in Figure 2-5.

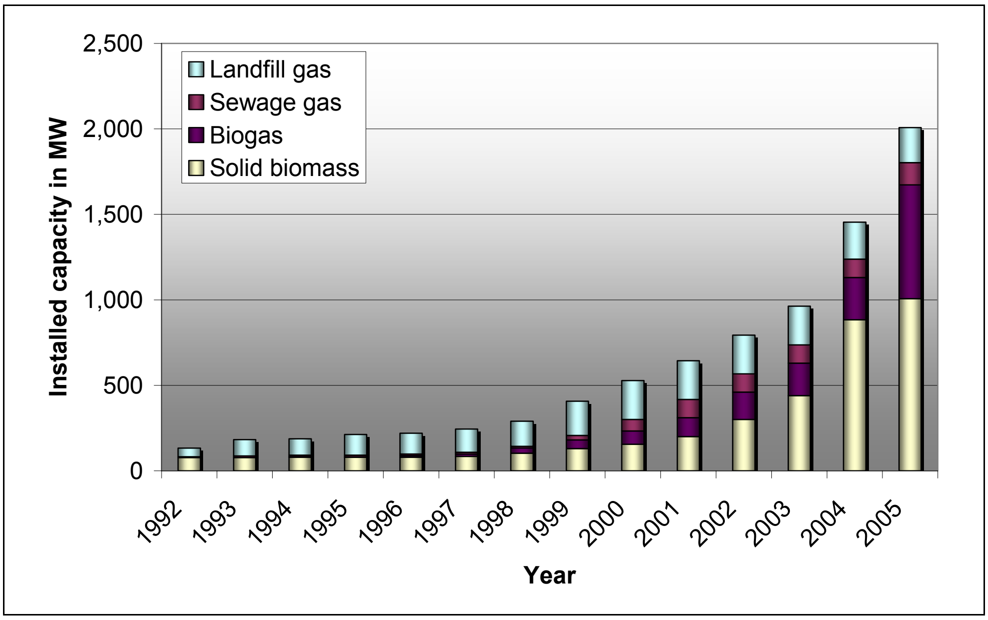

Figure 2-5: Development of biomass in Germany

Source: based on Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2006c, Institut für Solare Energieversorgungstechnik [ISET], 2006

2.5.3.2 Support

The support for biomass technologies was part of most German support schemes for renewable electricity generation technologies. In 1991 the Electricity Feed-In Law introduced a feed-in tariff of 80 % of the retail price (Bundesministerium für Wirtschaft und Technologie [BMWI], 1990, §3(1)). Additional support by capital grants and soft loans was provided by the Environment and Energy Saving Programme, the Market Stimulation Programme and the 100 Million Programme. In 2000 the Renewable Energy Act replaced the Electricity Feed-In Law and the tariff for solid biomass technologies was set to 87-102.3 Euro/MWh depending on the size (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2000a, §5). The tariff for sewage gas and landfill gas was set to 76.7 Euro/MWh. The annual reduction of the tariff was set to 1 %. In 2004 the Renewable Energy Act Amendment raised the tariffs for biogas and solid biomass to 84-115 Euro/MWh. Additional payments for CHP plants, selected fuels and selected technologies are available which can lead to tariff payments in the magnitude of 195 Euro/MWh (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2004a, §8). The risen support for biomass has accelerated the growth in the field of biogas and solid biomass. In two years the aggregate installed capacity for both technologies rose by more than factor two. An overview of the main support schemes for biomass is given in Figure 2-6.

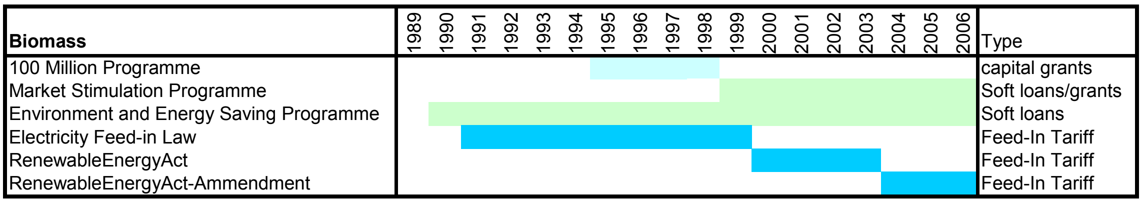

Figure 2-6: Main support schemes for biomass in Germany

Source: own illustration

2.5.4 Hydro and Geothermal power plants

In addition to the very dynamic development of the technologies presented above there are two additional technologies which are part of the German support scheme. Small hydro power plants have been part of most main support schemes such as the Electricity Feed-In Law, the Renewable Energy Act and the Environment and Energy Saving programme. This support has led to moderate growth of the installed capacity. However, the remaining potential for additional hydro power plants in Germany is limited. Therefore the growth is not as strong as for wind energy and PV. In 2004 large hydro power plants with a capacity of more than 5 MW were included in the German feed-in system by the Renewable Energy Act Amendment (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2004a, §6). Another technology which has been part of the German feed-in system since 2000 (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2000a, §6) is electricity generation by geothermal energy. However, this technology has not evolved beyond small demonstration plants. The slow development may be caused by the geological situation which requires considerable drilling depths of 1-5 km (Paschen et al., 2003, p.19) in most areas in order to reach adequate temperatures for the electricity generation. Although the estimations for the available potential of electricity generation are in the magnitude of up to

300 TWh per year (Paschen et al., 2003, p.51), it is not expected that geothermal electricity generation will play a major role in the electricity sector up to 2020 (Nitsch et al., 2005 p.19).

2.5.5 Consequences

The continuous support of renewable electricity generation has triggered a very dynamic development. Especially electricity generation by wind energy has become an important factor in the electricity sector because of its enormous growth through the past 15 years. Some of the renewable energy sources like wind energy and photovoltaics are characterized by fluctuating electricity generation which has to be taken into account. These fluctuations and the need to provide an adequate prognosis for this electricity generation are important factors in the electricity sector. As described in the introduction, the German feed-in support of electricity generation creates a number of interactions with the electricity sector which also affects some of the main developments described in this chapter. Renewable electricity generation reduces the demand for electricity generated by conventional power plants thus reducing the CO_2 emission of the electricity sector. Thereby the renewable electricity generation interacts with climate policy and the European emission trading system. Since renewable electricity generation reduces the remaining system load, it also has an impact on market prices of the electricity markets. On the other hand the fluctuating character increases the demand for system services. In addition the location of most wind power plants in northern Germany leads to a demand for extensions of the electric grid. As renewable electricity generation is privileged in a way that it has to be bought by grid operators to pass it on to the electricity suppliers, it also interacts with the process of liberalization. Another factor is that renewable electricity generation affects the utilization and deterioration of existing power plants. The major effects of renewable electricity generation on the electricity sector will be discussed in detail in Chapter 6.

2.6 Conclusion

The overview of the main developments within the electricity sector and the interactions of the renewable support scheme shows the complexity of the situation. Thereby it is important to note that the framework conditions of the electricity sector have changed since it was first established. With the exception of the regulated electricity grid the process of the liberalization of power production and consumer markets has moved the electricity sector from centralized planning in regional monopolies to the market-based interaction of different players. Thereby the support for combined heat and power plants and renewables and the nuclear phase out have a considerable impact on the competition between the different generation technologies. This situation gets even more complex as a consequence of the evolving CO_2 emission trading system. The CO_2 emission trading system has added a new factor to the calculation of generation cost for power plants. Besides the complexity of the given situation it is important to note that the considerable change of the framework conditions becomes an important factor itself. This process of changing framework conditions is likely to continue as new allocation plans for the emission trading system are developed and new rules for markets such as the balancing market are determined by the regulating authorities.

Since the goal of this thesis is to quantify the main interactions of the German support scheme for renewable electricity generation with the electricity sector, it seems to be advisable to utilize the support of a computer model. Especially the fluctuating character of renewable electricity generation calls for an analysis on an hourly level which can hardly be carried out without the support of a computer model. As an example for the fluctuating character of wind energy the electricity generation by wind energy in the year 2005 is given in Figure 2-7. The fluctuating character and regional distribution of electricity generation by wind energy increase the complexity of the situation and raise a number of issues. Due to the regional concentration of wind energy in northern Germany electricity transport and the requirement of extensions of the electricity grid have to be considered. Another issue is the impact of the fluctuation character of wind energy on the operation of power plants and the balancing of the system.

Due to the importance and complexity of the electricity sector a number of modelling approaches have been developed. The next chapter will provide an overview of the main modelling approaches in the electricity sector in order to provide a background for a decision on the applied approach. Thereby it is important to note that the developed modelling approach also has to deal with the complexity of the situation and the fact that the framework conditions are changing considerably over time.

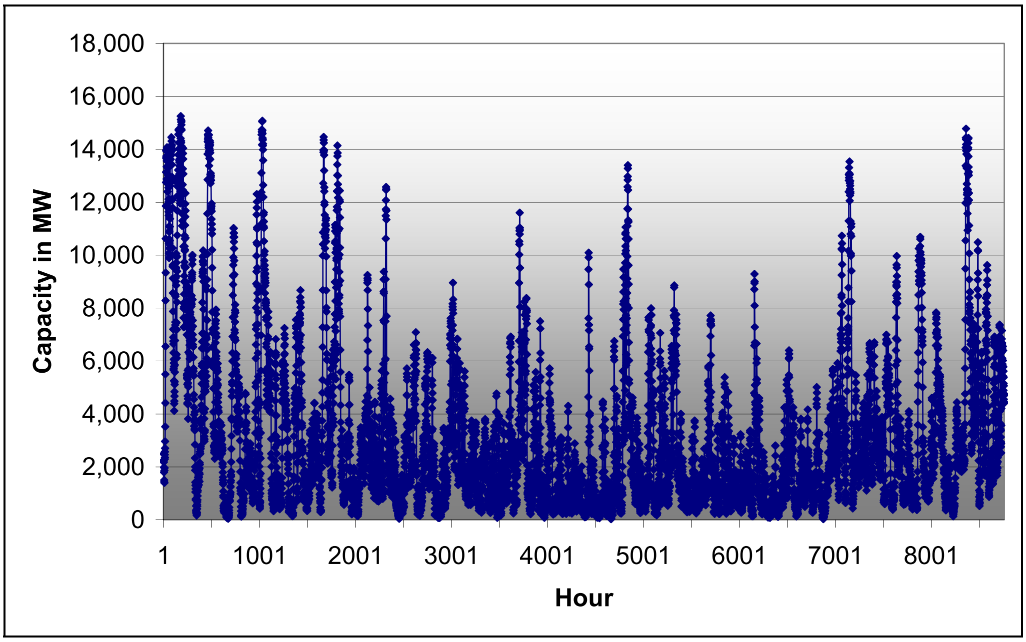

Figure 2-7: Electricity generation by wind energy in the year 2005

Sources: Based on Institut für Solare Engergieversorgungstechnik [ISET] and Gesamthochschule Kassel, 2005)

3 Approaches to modelling the electricity sector

The previous chapter has shown major developments in the electricity sector. On the given framework conditions the goal of this thesis to analyse the complex interactions of supported renewable electricity generation and liberalized electricity markets is a demanding task. A major result of the analysis carried out in the previous chapter is that the application of a computational model seems to be necessary. Due to the complexity of the electricity sector various approaches have been developed for the computational analysis of the electricity sector. The analysis of the impact of renewable electricity generation on the electricity sector is a demanding task which requires a careful selection of the applied modelling approach. The central goal of this chapter is to select the most suitable modelling approach. In a first step criteria for the evaluation of the analysed modelling approaches are developed. In a second step a general overview of the analysed modelling approaches is given. Thereafter the most relevant modelling approaches are discussed. Finally the most suitable modelling approach is selected in the conclusions of this chapter.

3.1 Criteria for the selection of the most suitable modelling approach for the given task

The selection of the most suitable modelling approach has to take the framework conditions into account.

Thereby it is important to note that the market price on the German spot market for electricity varies on hourly level. Other issues are the fluctuating character of renewable electricity generation and the variations of the load profile of electricity demand. As a result the plant dispatch and the resulting CO_2 emissions vary on hourly level, too. In the given context the balancing of the system also has to be considered. Therefore an essential requirement for the selection of the modelling approach is that the model has to be capable to deal with a high level of **technical detail**.

The analysis carried out in the previous section shows that the framework conditions of the electricity sector are subject to considerable changes over time. The political framework, the emergence of markets and new market rules can have a considerable impact on the electricity sector. In order to deal with these aspects in the context of the analysis of the impact of renewable electricity generation on the electricity sector, **flexibility** is an important criterion for the selection of the modelling approach.

As a result of the process of liberalization various markets have evolved where electricity and balancing services are traded. Among these are the spot market, markets for reserve capacity and the market for consumers. Since these markets interact, the model has to be capable to provide a realistic representation of **multiple markets** such as the spot market or the reserve markets.

Another important result of the liberalization is that the organization of the electricity sector has moved from centralized planning for regional monopolies to a market orientated interaction of several players. In order to be able to produce realistic market results and analyse the impact on different players, the model has to be capable to integrate the **perspective of single players**.

Furthermore the decision on the modelling approach should also consider some aspects related to the availability of models and the framework conditions for an own model development or extension. Therefore it is important to regard the **existing experiences** with the selected modelling approach. Is it commonly used for similar tasks? Are there any tools which simplify the model development process?

As a result of this analysis the following criteria are used for the analysis of the existing modelling approaches:

- capability to integrate a high level of technical detail
- flexibility
- capability to integrate multiple markets
- capability to integrate the perspective of single players
- existing experiences.

3.2 General overview

Due to the complexity of issues related to energy supply and demand various computational approaches to modelling energy supply and demand have been developed. In general energy models can be divided into two the categories of bottom-up models and top-down models (see also Nyboer, 1997, p.10; Enzensberger, 2003). The top-down approach takes a macroeconomic perspective and seeks to model developments within the entire economy. In many cases the broader perspective of top-down models requires the use of aggregate indicators instead of explicit technology options like single power plants. Important classes within the field of top-down models are Input-Output [I/O] models and Computable General Equilibrium Models [CGE]. Important categories of bottom-up models are optimisation and simulation models which also include the concept of agent-based simulation. A structural overview of the different modelling approaches presented in this chapter is given in Figure 3-1.

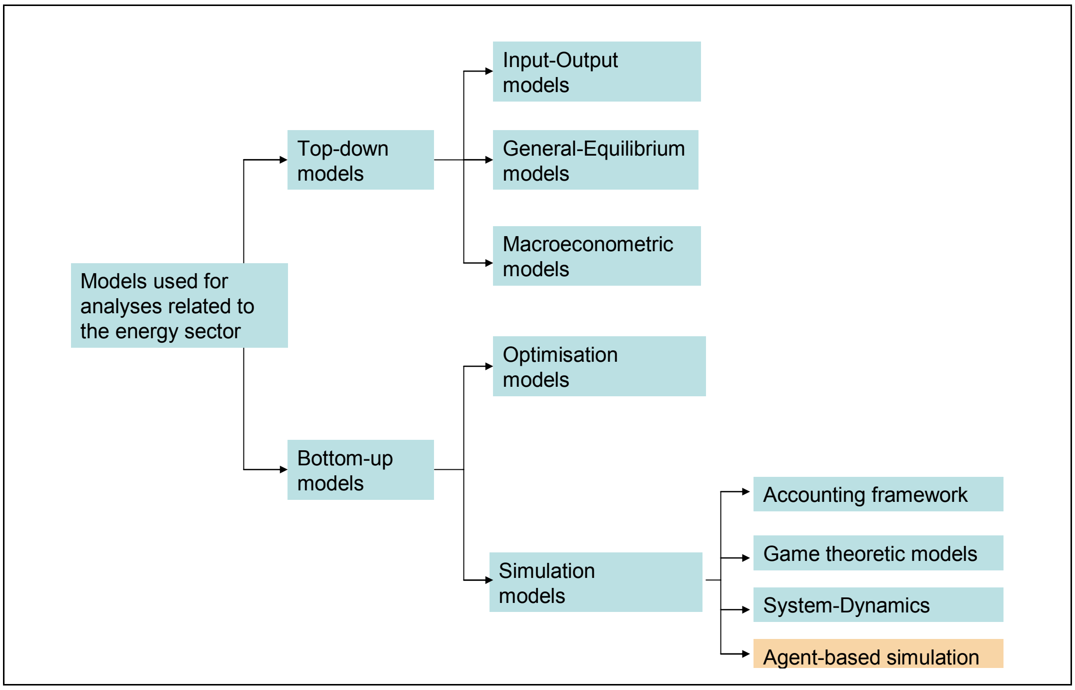

Figure 3-1: Overview of approaches to energy modelling
Source: own illustration

The overview of the modelling approaches applied to the analyses related to the energy sector shows that various modelling approaches exist. The general purpose of the modelling approach and the developed criteria can help to narrow down the choice of the modelling approaches.The general purpose of top-down models is the analysis of macroeconomic effects. A short overview of the characteristics of the important top-down modelling approaches is given in the following bullet points:

- **Input/Output models**: The central application of input-output models with regard to energy and environmental issues is the analysis of impacts on the economy resulting from given policies, e. g. CO_2 taxation (see Wietschel, 2000, p.241, Enzensberger, 2003, p.42). In general input-output models are used to analyse the development of economic indicators caused by exogenous changes in the sectoral demand of the economy (Kemfert, 1998, p.79).
- **Computable General Equilibrium models**: Since CGE models are based on the neoclassical concept of long run equilibria they can be used for long-term simulations. Due to their consistent equation system and their capability to integrate the government sector CGE models are applied in many cases to analyse the macroeconomic impact of environmental policies such as carbon taxes (Zhang and Folmer, 1998, p.115, Wietschel, 2000, p.239).
- **Macroeconometric models:** A common feature of macroeconometric models is the extensive process of empirical validation. In many cases macroeconometric models are applied to generate a short or long-term prognosis of economic development. In principle macroeconometric models are also capable to integrate aspects of environmental policies. Macroeconometric models can deviate from the assumption of perfect markets. The parameters used in equations to integrate imperfect market behaviour are econometrically estimated on the basis of long run time series of economic data (Kemfert, 1998, p.113).

The presented characteristics of the top-down approaches show the broader perspective of these models. A list of selected top-down models is given in the Appendix. The macroeconomic perspective leads to a reduction of the level of technical detail. Although there are some developments to increase the level of technical detail of top-down models (Böhringer, 1996, p.82), it can safely be stated that the macroeconomic orientated models are not well suited for the analysis carried out in this thesis due to the different scope and the lack of technical detail. Therefore the following analysis of the available modelling approaches will focus on bottom-up models which in many cases allow for a high level of technical detail.

3.3 Bottom-up models

The bottom-up approach seeks to model the development of energy systems based on a detailed representation of technological or economical developments. Important classes within the field of bottom-up models are optimisation models and simulation models.

3.3.1 Optimisation models

Optimisation models or energy system models focus on the analysis of the energy sector. Other parts of the economy are not taken into account. Due to the fact that most optimisation models only match energy supply and demand they are also called partial equilibrium models (Hourcade and Robinson, 1996, p.864; Enzensberger, 2003, p.45). Energy system models rely on detailed techno-economic data of single technology options like single power plant units. Optimisation models can be applied to maximize the economic surplus of producers and consumers on a single market. In many cases the energy demand is assumed to be inelastic, thus reducing the optimisation problem to a cost minimisation problem for a single player of the entire energy system (Böhringer, 1996, p.57). This approach is also called least cost approach or least cost planning. A central underlying assumption of optimisation is the precondition of a perfect market with perfect information (Nyboer, 1997, p.14). Additional boundary conditions like emission budgets are applied in many cases. As the given approach optimizes the energy system on given conditions, e. g. of the rest of the economy, the approach of optimisation models is also called normative. Depending on their capability to integrate intertemporal effects into the optimisation routine, optimisation models are called dynamic by incorporating a perfect foresight perspective or quasi-dynamic with a myopic (stepwise) optimisation of time periods without consideration of future developments (Schlenzig, 1997, p.50).

3.3.1.1 Application

A central strength of optimisation models is the capability to show explicit technological developments with a high level of detail. Therefore energy system models are applied in various applications ranging from the optimisation of capacity expansion planning for a single utility to the optimisation of the entire energy system of a single country or entire regions. Since energy systems require estimations on detailed techno-economic data such as efficiencies and cost of future technology options, the timeframe of analyses carried out with the given approach is in most cases limited to a period of up to 50 years. Most of the energy system models route back to the basic models EFOM (see also Rentz et al., 1995; Wietschel, 1994), MARKAL (see also Egberts, 1981) and MESSAGE (Schrattenholzer, 1981; Messner and

Strubegger, 1995). Examples for recent developments are BALMOREL (see also Ravn, 2001; Cremer, 2005); PERSEUS and TIMES. An overview of some examples is given in Table 3-1.

Table 3-1: Overview of selected energy system/optimisation models

Abbreviation	Complete name	Additional information
EFOM	Energy Flow Optimisation Model	Risø National Laboratory http://www.risoe.dk/sys/esy/models/efom_chp.htm
MARKAL	Market Allocation Model	Energy Technology Systems Analysis Programme (ETSAP) http://www.etsap.org/reports/markal.html
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact	The International Institute for Applied Systems Analysis (IIASA) http://www.iiasa.ac.at/Research/ECS/docs/models.html#MESSAGE
TIMES	The Integrated MARKAL-EFOM System	Energy Technology Systems Analysis Programme (ETSAP) http://www.etsap.org/Tools/TIMES.htm
BALMOREL	Baltic Model of Regional Electricity Liberalization	Risø National Laboratory http://www.risoe.dk/sys/esy/markets/balmorel.htm
PERSEUS	Programme package for Emission Reductions Strategies in Energy Use and Supply	Institute for Industrial Production (IIP), Universität Karlsruhe (TH) (Enzensberger, 2003)

3.3.1.2 Weaknesses

A central weakness of optimisation models is the tendency to underestimate cost related to changes in the energy system. The penetration of new technologies is often overestimated. This tendency is caused by the underlying assumption of a perfect market. Therefore common real world phenomena like information cost, transaction cost, gaming of markets and market failures are not integrated into pure optimisation models. (Zhang and Folmer, 1998, p.105; Gerdey, 2002, p.9; Wietschel, 2000, p.133). Especially in cases where energy demand is integrated into the analysis optimisation models tend to show a considerable potential for energy saving at low cost "no-regret-potential" which is not utilized in the real world due to the factors stated above. This phenomenon is also called "efficiency gap" (Hourcade and Robinson, 1996, p.865). An issue related to these effects is the fact that behavioural changes of individuals which can impact the energy sector cannot be integrated into technology orientated optimisation models. Another weakness of pure optimisation models is the separation of the energy sector from the rest of the economy. As a consequence macroeconomic feedbacks on the energy system e. g. by demand-price interactions are not integrated. An example for a macroeconomic feedback also called "rebound effect" could be that higher energy prices lead to lower energy demand thus influencing the structure of energy supply. Another issue related to optimisation models is the "penny-switching" effect (Schlenzig, 1997, p.89) which occurs if small changes of the input data lead to completely different results because the optimisation routine always selects the cheapest technology even if price differences are very small. Another criticism of complex large scale optimisation models is the fact that the model results are sometimes difficult to understand (Schlenzig, 1997, p.63), especially if various boundary conditions are applied. Depending on the level of detail optimisation models require extensive techno-economic data on explicit technology options which can be rather difficult to obtain.

3.3.2 Simulation models

Another class of bottom-up models are simulation models. In contrast to equilibrium models simulation models do not have to rely on a closed equilibrium framework (Ventosa et al., 2005, p.905). Instead simulation models rely on a set of rules that define single processes within the model (Borshchev and Filipov, 2006). This approach allows a stepwise development of computational models of very complex and time dependent systems. Since the concept of simulation models is very flexible a broad range of modelling approaches can be grouped in this category. Thereby simple accounting frameworks are included as well as potentially very complex approaches such as system dynamics or agent-based simulation. In the context of this thesis game theoretic approaches are grouped in this category as well because some developments e. g. by Day and Bunn (Day and Bunn, 2001) with a repeated interaction of players are very closely related to the concept of agent-based simulation.

3.3.2.1 Accounting frameworks

Accounting frameworks can be considered as a simple form of a simulation model. They are based on a physical and economic description of the energy system (Heaps, 2002, p.8). Instead of modelling decisions of players explicitly this type of model accounts for the outcomes of the assumed development (scenario). A common application of this approach is the projection of future energy demand and the corresponding emissions. Due to their simple structure these models can also be used for capacity building and the start up of modelling activities e. g. in developing countries. Examples for accounting frameworks are LEAP, MEDPro and MAED. Due to their simple structure accounting frameworks cannot be applied to the simulation of decision processes such as plant construction or price setting on a market.

3.3.2.2 Game theoretic approaches

Game theoretic approaches mainly focus on the interaction of players on markets. The applications of these approaches in the energy sector mainly focus on market design and the aspect of market power. An important part of game theoretic approaches is the analysis of stable equilibria, such as the Nash-equilibrium where no player can improve his own situation unilaterally with the given framework conditions. Important model types applied for the analysis of oligopolistic electricity markets are Cournot Models, Bertrand models and Supply Function equilibria models. Since many of these approaches are designed for oligopolistic markets of homogenous goods there are various examples dealing with electricity markets. Some examples are presented in this section.

In Cournot Models the strategic decision variable applied by players is the quantity bid into the market (Varian, 1999). There are several examples of Cournot models dealing with the electricity market. Stoft presents a Cournot model to analyse the impact of financial transmission rights on the market power of generators (Stoft, 1999). Another analysis of the impact of transmission constraints on a simplified electricity market is presented by Willems (Willems, 2000). Willems presents a simulation platform which can be used to analyse the impact of transmission allocation rules set by the system operator on the market power of generators.

Chuang et al. present a Cournot Model for the analysis of generation expansion planning in a liberalized electricity market (Chuang et al., 2001).

In contrast to Cournot models, Bertrand models use the price as strategic decision variable (Berninghaus et al., 2002, p.47). Both approaches can lead to different results (Yao and Oren, 2006, p.1) whereas the Betrand Model mostly results in prices closer to perfect competition than Cournot models (Lee and Baldick, 2003). A recent application to the analysis of electricity markets is a model presented by Yao and Oren proposing a hybrid Bertrand-Cournot model to the simulation of a simplified electricity market with special emphasis on the transmission situation and the resulting prices (Yao and Oren, 2006).

An extension of both approaches is the concept of supply-function equilibria models. In supply function-equilibria models every player bids a supply function which is a combination of prices and corresponding quantity into the market. Many recent publications on supply function equilibria models are inspired by a paper published by Klemperer and Meyer (Klemperer and Meyer, 1989). Klemperer and Meyer argue that under uncertainty a single focus on price or quantity may not be the best strategy for a company. They argue that the supply-function as a combination of price and corresponding quantity offers better opportunity to adapt to an uncertain environment. However, the calculation of a supply function equilibrium is a demanding task. The authors have to make strong assumptions in order to prove a unique equilibrium such as linear demand and marginal cost functions. Many studies have extended and applied the given approach to the electricity sector. An interesting example is presented by Day und Bunn (Day and Bunn, 2001) who develop a sequential simulation where generation companies optimize their supply function on the assumption that competitors keep their supply function of the previous day constant. In order to include bounded rationality players can only adjust the bid price of not more than two plants. The supply function itself is restricted to be piecewise linear with bins of constant size across all companies. Another recent example for an extension of the supply-function equilibrium approach is the model presented by Anderson and Xu (Anderson and Xu, 2006). They present an approach to relax the condition of a linear supply function to a piecewise differentiable function in order to integrate the impact of option contracts.

3.3.2.2.1 Weaknesses

While the developed game-theoretic approaches are suited to analyse market structures in an analytical way, a realistic representation of the complex situation of real world electricity markets seems to be difficult. In general the developed models have to make strong assumptions in order to keep the model solvable or in line with the theoretical framework. While Cournot and Bertrand models have to reduce the decision process of a generation company to one variable (Day et al., 2002, p.600), supply-function equilibria have to simplify the competitive situation or the supply function itself (Bunn, 2000, p.167). However, the presented studies show that there is a continuous effort to reduce the necessary assumptions.

3.3.2.3 System dynamics

The approach of system dynamic [SD] models has been developed in the 1950s by the electrical engineer Forester (Forrester, 1958). Thereafter the system dynamics models have been used in a variety of applications. In system dynamics the energy systems are represented by stocks and flows. Stocks and flows are connected. The concept allows for an integration of changes over time, which enables the simulation of aspects like feed-back characteristics or delayed developments. In mathematical terms system dynamics models can be represented as a set of differential equations (Borshchev and Filipov, 2006, p.5). The basic concept of system dynamics allows for a variety applications reaching from technical simulations to the analysis of business dynamics of single companies (Forrester, 1991).

3.3.2.4 Applications

In the energy sector system dynamics models have mainly been used for the analysis of long-term developments. One of the most prominent examples of the application of system dynamics to energy issues is the work "Limits to growth" published by Meadows et al. (Meadows et al., 1972) which has drawn attention to the increasing demand for energy and resources. A rather complex system dynamics model for the analysis of the European transport sector called ASTRA-D is presented by Schade (Schade, 2004; Schade and Rothengatter, 2003). In the electricity sector many developments focus on the simulation of investment decisions for power plants. Among these is the work published by Bunn and Larsen (Bunn and Larsen, 1992) analysing the impact of competitive situation and reserve margins on capacity development. Later extensions of this approach have been applied to the analysis of investment decisions in the liberalized UK electricity sector e. g. (Gary and Larsen, 2000). In a recent example Olsina et al. have presented an approach which analyses the investment decisions in different load segments (Olsina et al., 2006) by the integration of price duration curves into a system dynamics investment model. In another approach the possible effects of market power in an interrelated gas and electricity market are analysed (Bunn et al., 1997). A further overview of the application of system dynamics models in the electricity sector can be found in (Ford, 1997)

3.3.2.5 Weaknesses

Since the system dynamics approach relies heavily on the characteristic of the designed feedback loops, the validation and calibration of these assumptions is a crucial issue determining the quality and reliability of the results (Enzensberger, 2003 , p.50). Another issue is that the approach is not designed for the explicit representation of the decisions of individuals and their learning processes (Schieritz and Milling, 2003).

3.3.2.6 Agent-based simulation

The concept of agent-based simulation is a relatively new field which evolved within the last 10-15 years. The concept seeks to overcome some of the weaknesses of conventional modelling approaches by building a simulation from a player's perspective which helps to integrate aspects like player strategies or imperfect information. A central strength of the agent-based simulation approach is its flexibility and the possibility to deviate from "normative" equilibrium conditions or strategies. As an example the modelling approaches such as optimisation models 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).

The approach of agent-based simulation draws on the concepts of several disciplines such as economy/game theory, social sciences and software engineering (Wooldridge, 2002).

The variety of approaches to agent-based simulation has led to a variety of definitions concerning the term "agent". One definition which is often quoted in the field of multi-agent systems or distributed artificial intelligence is given by Wooldridge and Jennings (Wooldridge and Jennings, 1995) stating that agents are characterized by autonomy (ability to operate on its own), social ability (ability to interact with other agents), reactivity (ability to respond to a perceived environment) and pro-activeness (ability to act on its own initiative in order to reach envisaged goals). A review of different definitions of the term "agents" by Franklin and Graesser leads to the following definition of the essence of the term "agent":

"*An autonomous agent is a system situated within and a part of an environment that senses that environment and acts on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future"* (Franklin and Graesser, 1996, p.5).

However, a review of agent-based simulation platforms shows that the agents used in these simulations in many cases apply weaker definitions of the term "agent" (Drogoul et al., 2002). The agent-based analysis of economic systems is called "Agent-based Computational Economics". According to Tesfatsion (Tesfatsion, 2006) the term "agent" refers to an entity of a computational world which can be characterized by bundled data and behavioural methods. Thereby agents can represent individuals, institutions or physical entities.

The discussion on the actual definition of the term "agents" within the field of agent-based simulation shows that it is difficult to get a grip on the term "agent-based simulation" from the normative perspective. In the given context of this thesis it seems to be more relevant to have a closer look at the advantages and disadvantages of agent-based simulation. An overview of applications of agent-based simulations to the electricity sector is given in the next chapter. Similar to the system dynamics approach the crucial issue is the empirical validation of the developed models.

3.4 Conclusions

The last step of the analysis of the selected modelling approaches is the evaluation according to developed criteria. An overview of the assessment of the described modelling approaches according to the given criteria is shown in Table 3-2.

Table 3-2: Evaluation of the modelling approaches for the given task

Model	Technical detail	Flexibility	Multiple markets	Players' perspective	Existing experiences
OM	+	0	–	–	+
AC	+	+	–	–	+
GT	–	0	0	+	+
SD	+	+	+	0	0
ABS	+	+	+	+	–

Legend: + good 0 medium – weak
OM = Optimisation models
AC = Accounting frameworks
GT = Game theoretic approaches
SD = System dynamics
ABS = Agent-based simulation

The requirement of high technical detail level rules out most Top-down models which are not designed to deal with this level of detail. Flexibility in the given case means that the model can be extended easily or adjusted to new framework conditions. Based on the gathered information, most simulation models perform well according to this criterion. Exceptions are game theoretic models which seem to be more difficult to adjust to new conditions. Optimisation models and accounting frameworks do not seem to be well suited for the modelling of e. g. several electricity markets since these models are not designed for the explicit modelling of several markets where different players interact. However, system dynamics and agent-based simulation models seem to be well suited for the explicit modelling of multiple markets.

Another important criterion is the ability to integrate the perspective of different players into the simulation. Accounting frameworks and optimisation models are not designed for this purpose. A similar situation occurs for system dynamics models. Although these models are very flexible, they are not well suited for the integration of the perspective of single players e. g. by integration of learning algorithms. So they do not seem to be well suited for the integration of the perspective of different players into the analysis. Agent-based simulation and game theoretic models seem to be well suited for this task since they are explicitly designed for this purpose.

The last criterion to be considered in the model selection process is the existing experience with modelling approaches. Most established modelling approaches can rely on a considerable community of scientists and a variety of existing tools and models. Although system dynamics models are wide spread, they do not seem to be as established as the other approaches. Since agent-based simulation is a relatively new concept, the existing experiences with this approach are rather limited compared to the presented alternatives.

However, the concept seems to be well suited in all other criteria selected for this analysis. Thereby its flexibility and capability to integrate the perspective of single players are the most important strengths for the task of this thesis. Therefore the concept of agent-based simulation is selected for the analysis carried out in this thesis. The drawback of the missing support of a strong and established modelling community is the price to be paid for this decision. However, the application of agent-based simulation to the analysis electricity markets is a field which has rapidly evolved throughout the past few years. The next chapter provides an overview of the main developments within the field of agent-based simulation of electricity markets.

4 Agent-based simulation of electricity markets

As described in Chapter 2, the electricity sector in Germany and Europe is undergoing considerable changes. The same is true for other regions of the world like the USA. The liberalization 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 (US-Canada Power System Outage Task Force, 2004) have changed the way electricity markets are regarded. Based on these circumstances new questions arise: How can liberalized 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 framework conditions are necessary that new players can enter the market? Which policies are adequate to ensure environmental goals like climate protection and promotion of renewable energy on 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 simulation platforms.

As discussed in the previous chapter, two central strengths of the agent-based simulation models are their flexibility and the possibility to deviate from "normative" equilibrium conditions or strategies.

These advantages of agent-based simulation models have led to an increasing popularity of the approach in the community of electricity market modellers. This development is triggered by the additional opportunities that this modelling approach offers for the analysis of economic systems in comparison to more traditional equilibrium models or optimisation models. Among these are aspects like learning effects in repeated interactions, asymmetric information, imperfect competition, or strategic interaction and collusion which can be included in a more realistic way in agent-based models. Also, the agents' individual behaviour and their interaction can be integrated more freely than in optimisation and equilibrium models. Increasingly powerful computational resources as well as the development of toolkits for the implementation of agent-based models in object-orientated programming languages have further increased the popularity of agent-based simulation models. 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 of realism.

As consequence of the novelty of the approach of agent-based simulation there is no standard work on the current status of agent-based simulation of the electricity sector. The central goal of this chapter is to provide an overview and a systematization of the recent work in the field of agent-based simulation of electricity markets. As this research area evolves in a very dynamic way, the presented review cannot ensure completeness. However, care has been taken to include the most relevant publications that are known to the author[1]. 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. In order to provide a structure for the literature survey, the reviewed papers are grouped into three main categories of ongoing research: 1. Analysis of market power & design, 2. Modelling agent decisions 3. Coupling of long-term and short-term decisions. The chapter 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 4-1.

However, it has to be pointed out that there is some overlap between these categories (see also Figure 4-2 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. 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.

1 This chapter is the result of an extensive literature review submitted for publication to Energy Studies Review: Sensfuß et al. (2007a). The text of this Chapter is written by the author by this thesis only.

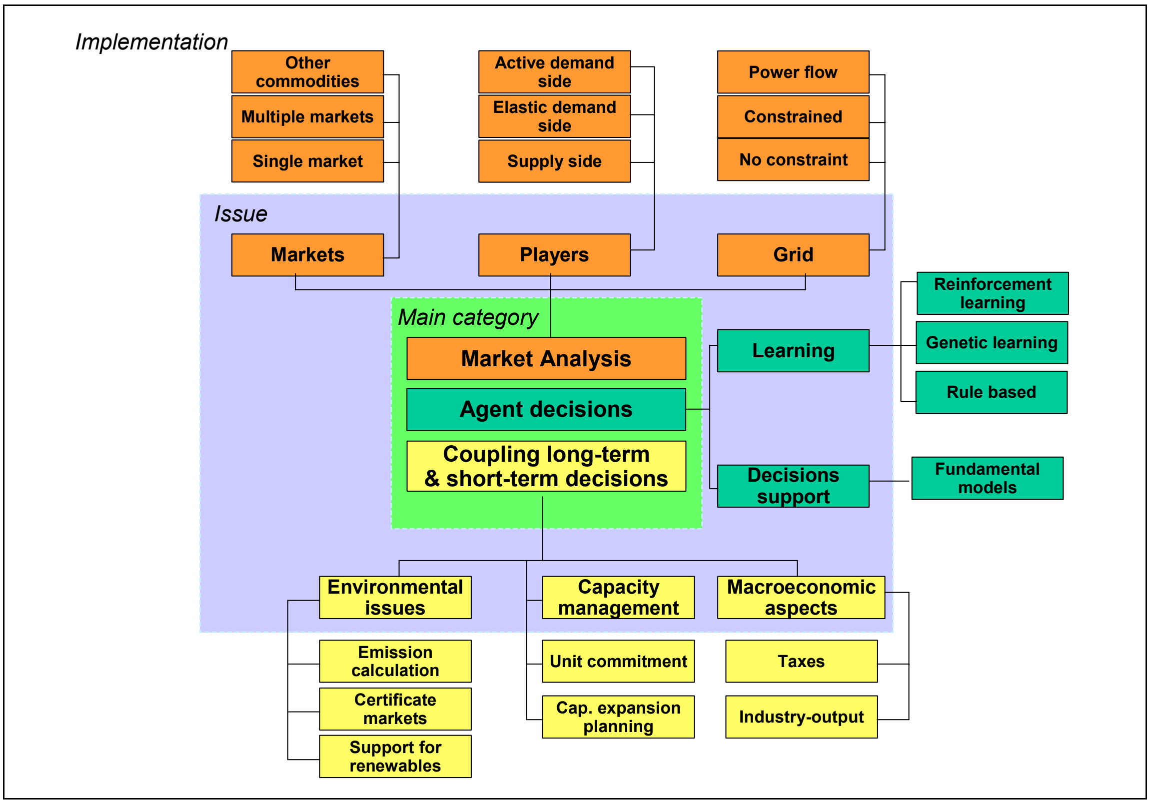

Figure 4-1: Overview of main categories and different contributions of ongoing research on agent-based simulation of electricity markets

Source: own illustration

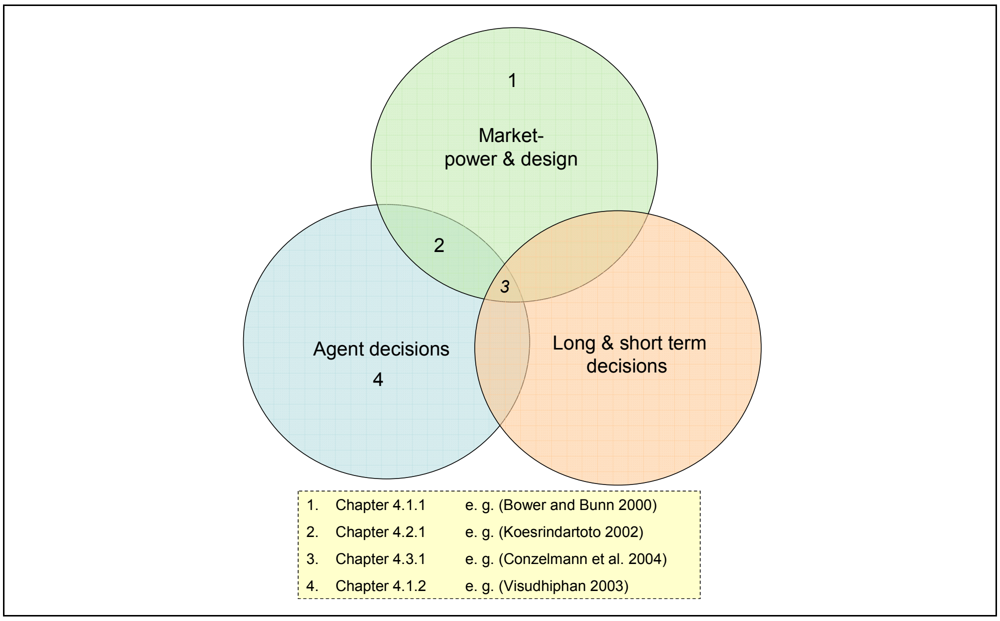

Figure 4-2: Overview of the main research categories in the reviewed literature

Source: own illustration

4.1 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 4-3.

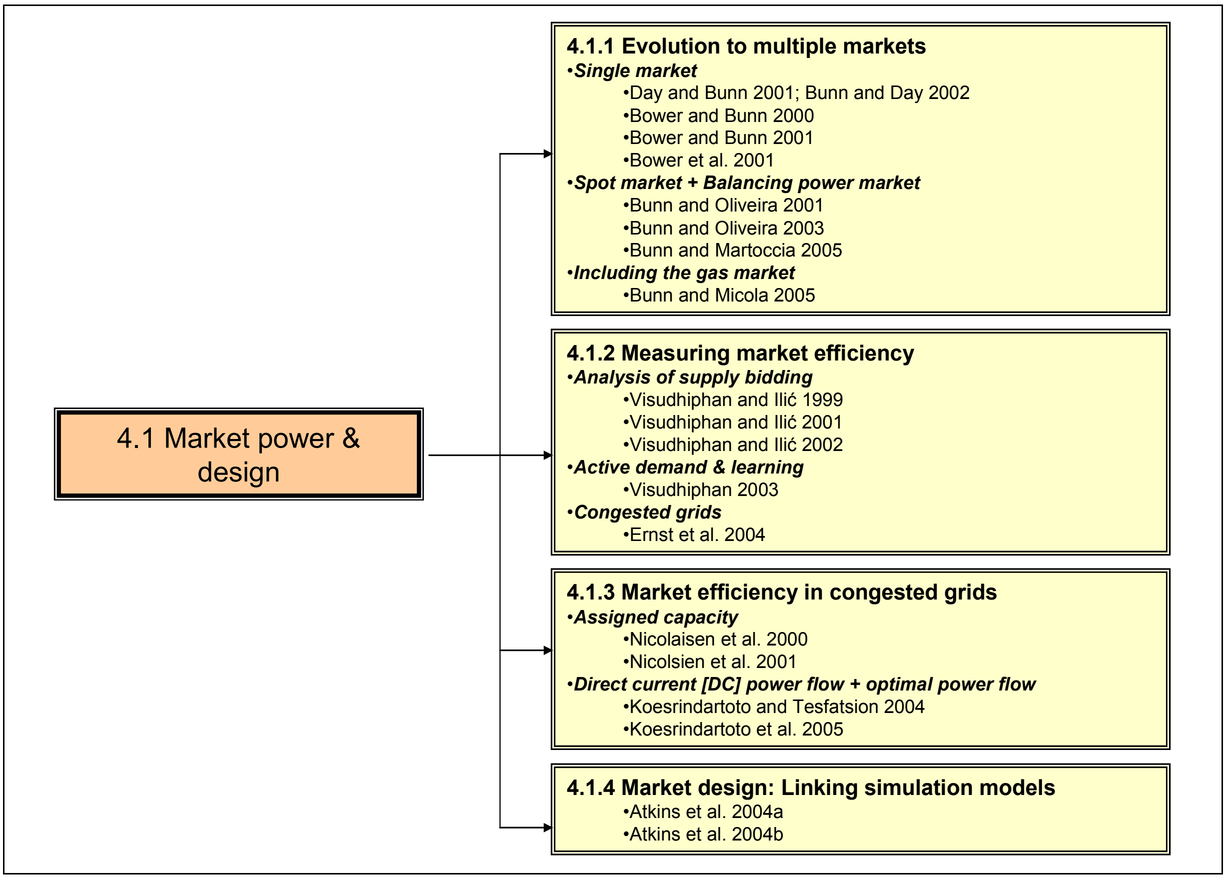

Figure 4-3: Overview of reviewed papers on market power and design
Source: own illustration

4.1.1 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 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 the 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 (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 due to the mathematical problems concerning the calculation of the equilibrium[2]. The computational model is then applied to analyse different options for the second round of plant divestment 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 maximize profits and to reach a given utilization rate of a power plant. The agents can choose between four strategies, e. g. lowering prices when the expected utilization 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 where the individual bid price is paid for successful bids leads to higher prices than uniform price settlement where the marginal bid sets the market price for

2 see also Chapter 3.3.2.2

all bids. Another finding is that a shift from daily bidding with a single price for the entire day 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 Electra/Bayernwerk creating Germany's biggest electricity utilities is analysed in different simulation settings including plant closures and lower utilization 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[3], where price is the strategic decision variable, 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

3 see also Chapter 3.3.2.2 for more information on Betrand models

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).

4.1.2 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 Ilic, 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 base load 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 Ilic, 2001) report on simulation results of a model in which adaptive agents can show strategic behaviour and learn to improve their bids. The research issue 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 to 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 Ilic, 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 maximization problems. In the same way as in the previous paper the short-term bidding strategy is split into a 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 (Visudhiphan, 2003). 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 (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.

4.1.3 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 contributions range from the analysis of market power to the analysis of agent learning (see also 4.2.1).

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 customers 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 gets 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 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 proved. 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 wholesale power markets in the USA. 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 linear constraints. The formulation of the transmission 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 behaviour in relation to short-term and long-term market performance.

4.1.4 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., 2004b; Atkins et al., 2004a). 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)[4] are analysed in combination with different trading strategies (1. competitive, 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.

4 *"Normal" = uniform clearing* = marginal bid determines the price for the entire market; *Vickerey clearing* = the price of the first bid above the marginal bid determines the price for the entire market; *Weighted average clearing*= the market price is determined as the weighted average of all dispatched asks.

4.1.5 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., 2004b; Atkins et al., 2004a) 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 (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., 2004b). One remarkable difference between most European projects and the projects carried out in the USA 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 USA, transmisison constraints are not integrated into 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 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.

4.2 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 4-4.

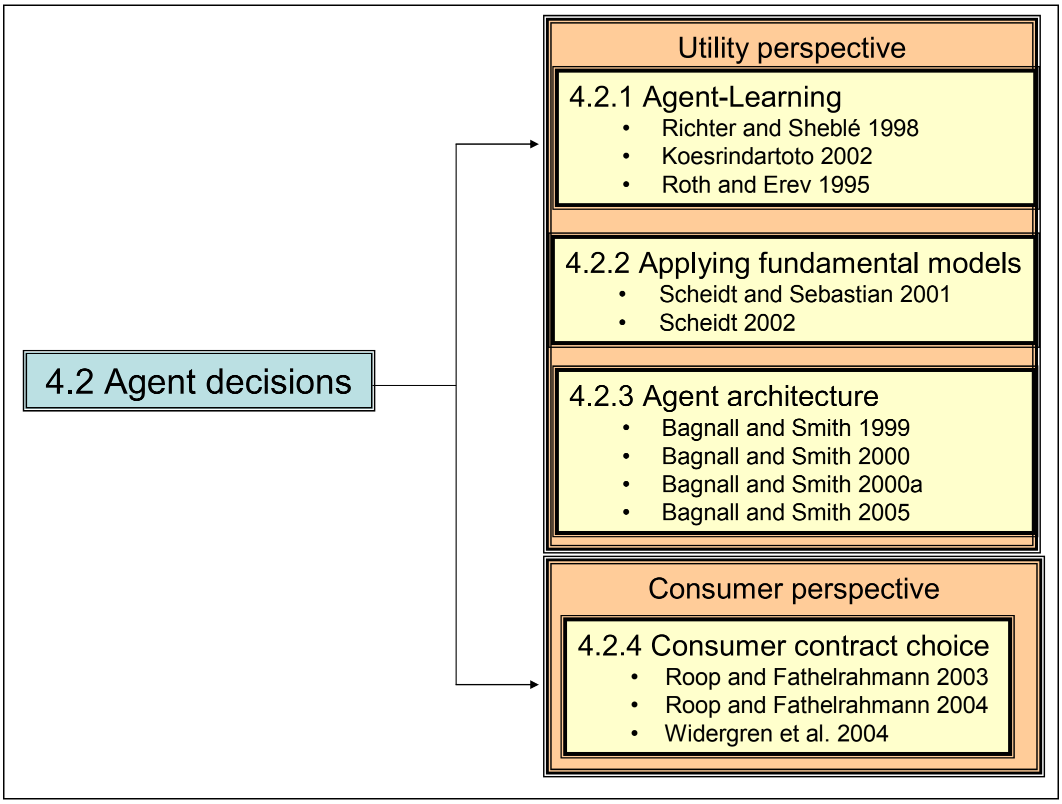

Figure 4-4: Overview of reviewed papers on agent decisions
Source: own illustration

4.2.1 Analysis of the impact of agent learning on simulation results

In order to provide a basis for the analysis of the aspect of agent learning, some important terms need to be defined. An overview of important terms used in the context of this analysis is given 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 performance of a rule 3. A rule discovery algorithm which creates new rules (see also Bagnall, 2000b, p.155 ff.).

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 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 strategies 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 where the price is determined as the midpoint between matched bids and offers. The matching procedure sorts the bids and offers and matches the highest bids with the lowest offers as long as the bid price is above the corresponding offer price. 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.

4.2.2 Application of fundamental models to support agent decisions

Another agent-based simulation project, which focuses 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 plays 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[5]. 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 transmission 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 is capable of buying and selling electricity, depending on the utilization 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 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 utilization. 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 are proprietary (Scheidt, 2002).

4.2.3 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, 2000b). 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 a

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

schedule without any constraints. 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 to analyse 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, 2000a), and a realistic market volatility (Bagnall and Smith, 2005).

4.2.4 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 Fathelrahman, 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 Fathelrahman, 2004).

4.2.5 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 reinforcement learning algorithms instead of pure genetic algorithms.

4.3 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 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 chapter also describes some of the concepts for the development of an agent-based simulation platform at the Universität Karlsruhe (TH). 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 4-5.

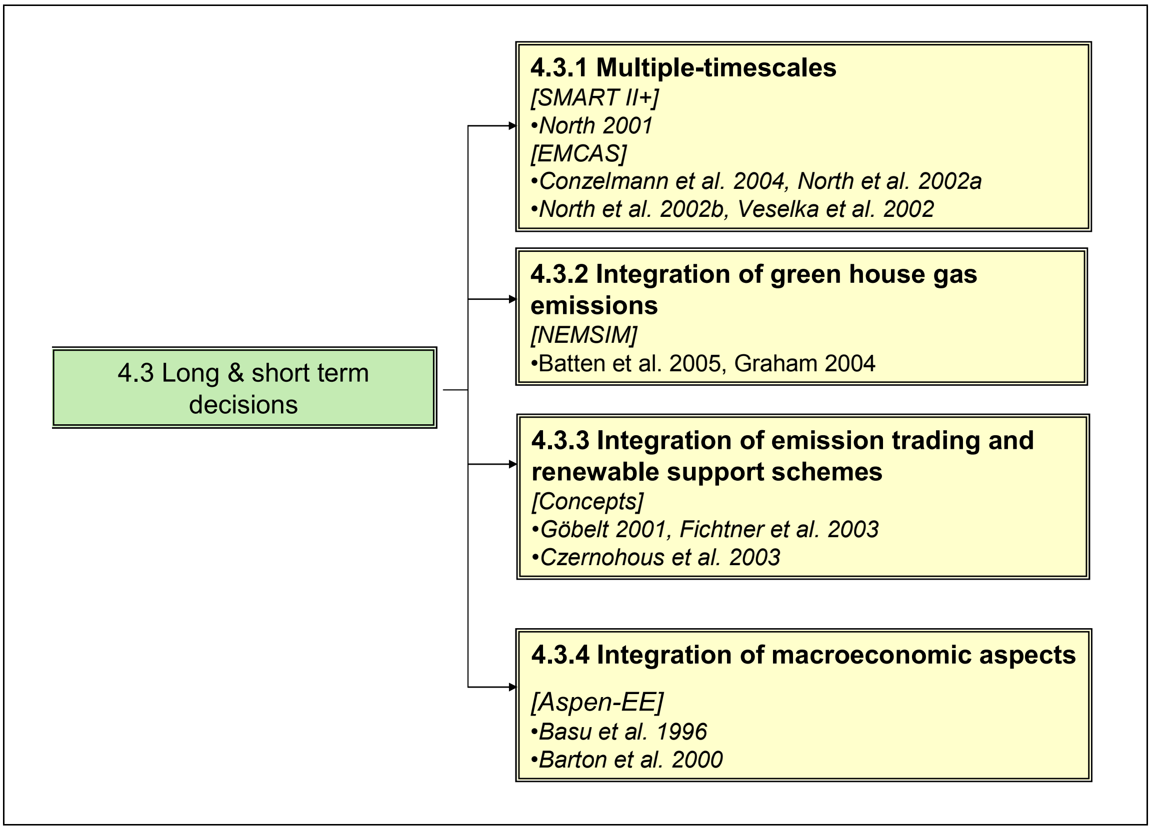

Figure 4-5: Overview of the reviewed literature in this section

Source: own illustration

4.3.1 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 (North, 2001). 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 market place. 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 being 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.

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

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) develops an agent-based simulation called NEMSIM 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 author, 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).

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

Since 2000/2001 several approaches of agent-based energy models have been designed at the Universität Karlsruhe (TH) and the Fraunhofer Institute for Systems- and Innovation Research of Karlsruhe. 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 proposes 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. These developments paved the way for the development of the agent-based simulation platform PowerACE. It will be described in more detail in the next chapter.

4.3.4 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.

4.3.5 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.

4.4 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 4-6.

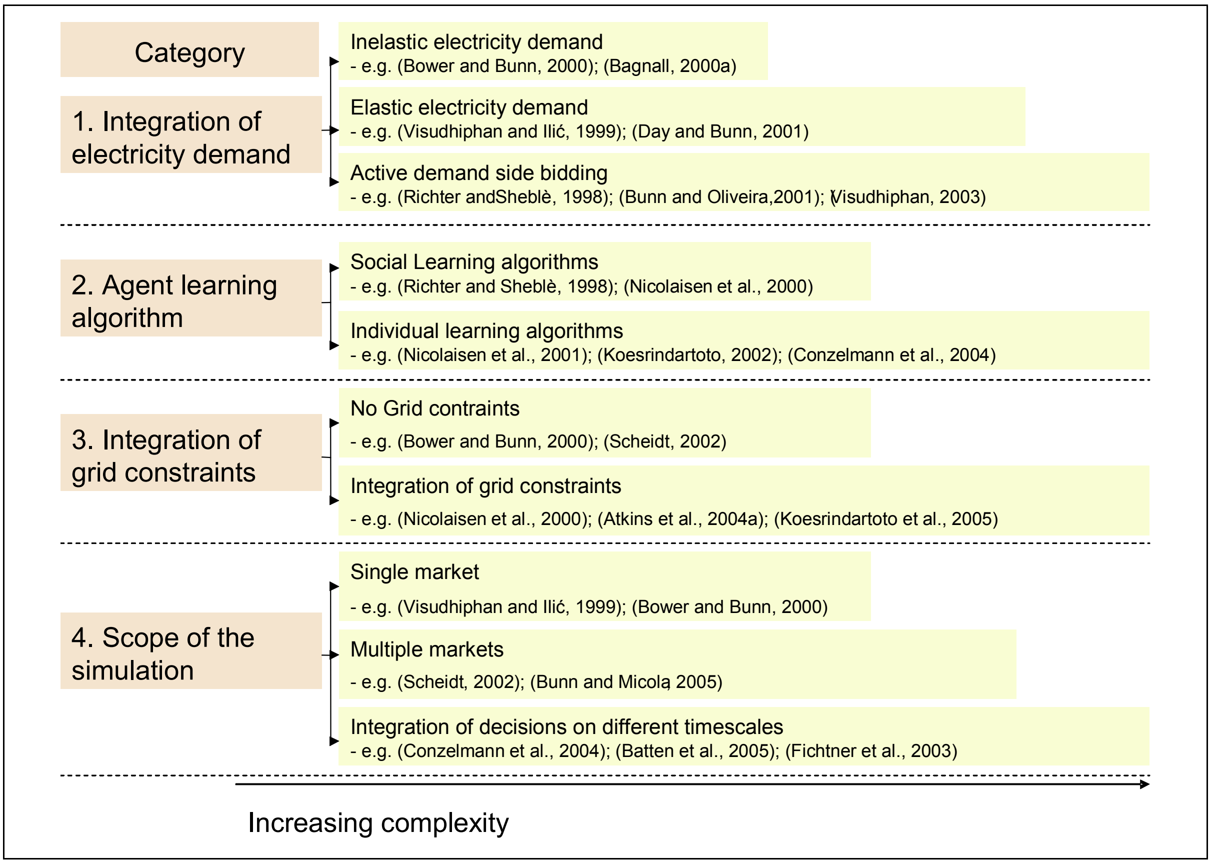

Figure 4-6: Examples for the increasing complexity of agent-based simulations
Source: own illustration

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 utilization 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 grid infrastructure. However, rising electricity demand, the goal to create a European electricity market with increased cross border trades and the integration of large scale offshore wind energy also raises grid issues in Europe (Deutsche Energie-Agentur [DENA], 2005).

As the concept of agent-based simulation is applied to large scale simulation platforms, such as EMCAS 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 (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. Thereby the capability to integrate the players' perspective and the capability to simulate player interaction and learning allows for analyses which cannot be obtained by other modelling approaches.

Besides the analysis and systematization of the existing literature the central question within the context of this thesis is whether there is a promising model publicly available that can be used for the analysis of the impact of renewable electricity generation on the German electricity sector. Generally it has to be stated that the existing models have not yet reached the status of widely accepted programme packages which can be purchased or obtained free of charge. Therefore the situation is different to well established modelling approaches such as optimisation models where a number of freeware and commercial software packages such as BALMOREL of MARKAL (see also Chapter 3.3.1) is available.

Besides the availability of the existing software packages it has to be stated that the analysed models are not designed for the analysis of the impact of renewable electricity generation on the German electricity sector. There is no model available which is designed for the detail level required for the given task. None of the developed models has a special emphasis on renewable electricity generation such as a very detailed integration of the fluctuating load profile of wind energy for an entire year. The same is true for the representation of renewable support schemes and the utilization of pump storage plants within the simulation platforms. None of the analysed models takes the European emission trading scheme into account.

There are two models which deal with the German electricity sector. The model presented by Bower et al. (Bower et al., 2001) is mainly designed for the principal analysis of market power caused by the concentration in the German electricity sector. It lacks the necessary level of detail. The same is true for the model presented by Scheidt (Scheidt, 2002) which is tested with a synthetic data set only.

In order to be able to analyse the impact of the renewable electricity generation on the German electricity sector, the developed model has to be able to deal with a high level of technical detail and it has to be flexibe enough to be adjusted to the constantly changing framework conditions of the electricity sector. The high level of detail leads to new challenges concerning the management of data and computational resources. This analysis indicates that it is necessary to develop an own agent-based simulation platform which can be designed for the given purpose.The next chapter describes the development of the agent-based simulation platform PowerACE Cluster System designed for the analysis of the German electricity markets.

5 Development of the PowerACE Cluster System

The results of the analysis carried out in the previous chapters have shown that the concept of agent-based simulation seems to be an adequate concept for the simulation of the electricity sector in order to analyse the important effects of renewable electricity generation on the German electricity sector such as the interaction with the electricity market and the CO_2 market. The last chapter has shown the current status of agent-based simulation of the electricity market. The conclusion based on this survey is that it seems to be necessary and promising to develop an own agent-based simulation platform. This chapter describes the development of the PowerACE[6] Cluster System. The simulation platform consists of several modules dealing with electricity supply, demand, renewable electricity generation, electricity markets and the simulation of pump storage plants. A CO_2 market is integrated into the simulation platform, but not utilized within this thesis. An overview of the structure of the developed simulation platform is given in Figure 5-1.

In this chapter the developed modules are described in detail. At the end of the chapter the developed cluster system is presented and the capability of the model to produce realistic spot market prices is analysed in a calibration and benchmarking procedure.

6 The core of the PowerACE Cluster System is the PowerACE simulation model. The model is developed in cooperation with the Universität Karlsruhe (TH) and the University of Mannheim. The project is sponsored by the "Volkswagen Stiftung". The main developments carried out by the author of this thesis are: The simulation of electricity demand and renewable electricity generation, the development of the primary and secondary reserve markets, the simulation of pumpstorage plants, the simulation of the gridoperator and the entire PowerACE Cluster System with the related tools for automated data analysis and the management of computational resources and the necessary modifications of the PowerACE for the integration into the cluster system. The simulation of electricity supply applied in this thesis is a slightly modified version of the PowerACE supply module dealing with utilities, their power plants based on a detailed database, the creation of bids into the markets and the export and import of electricity. The PowerACE supply module was developed by Massimo Genoese (University Karlsruhe). The development of the basic spotmarket, the selection of the development software and the integration of XML-based setting files into the PowerACE model are the major contributions by Anke Weidlich (University Mannheim) to the PowerACE version applied in this thesis.

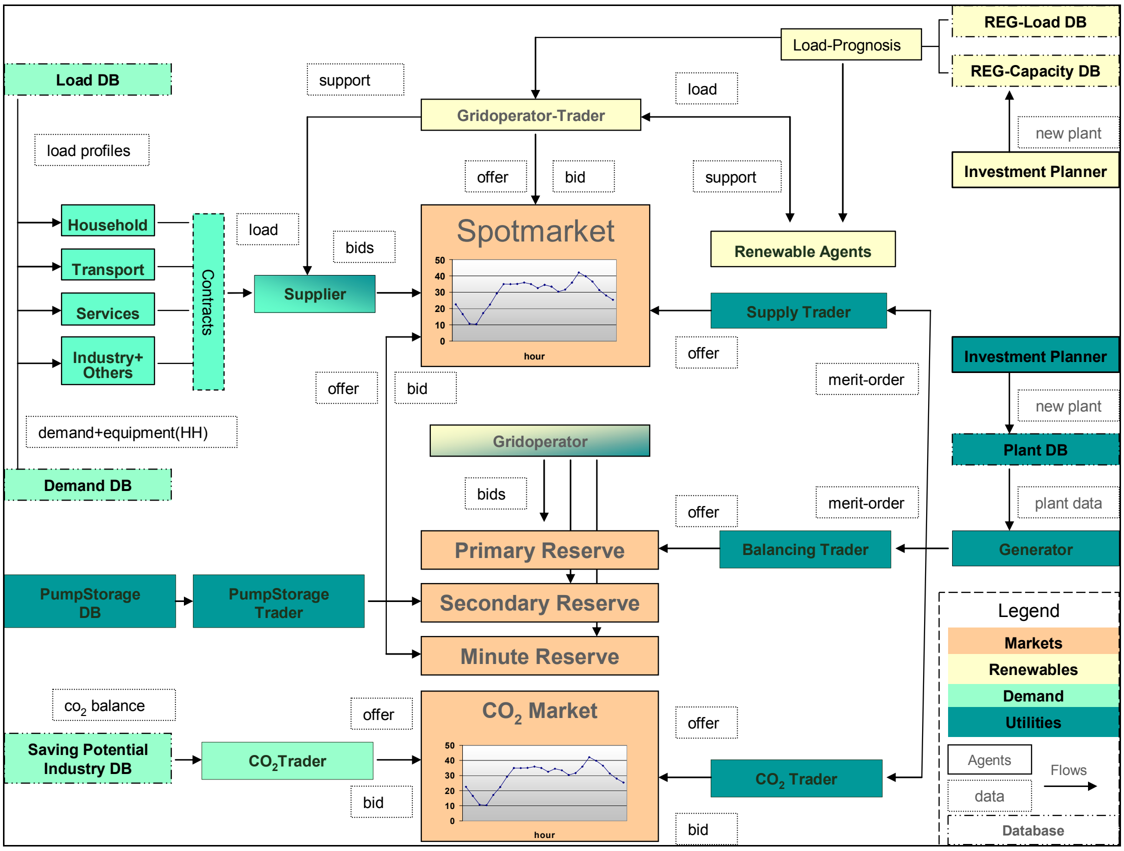

Figure 5-1: Structure of the PowerACE simulation platform

Source: own illustration

5.1 Simulation of electricity demand

An important part of the simulation of the electricity market is the representation of electricity demand. The simulation of electricity demand in the electricity sector is made up by two important tasks. The first important task is the creation of an adequate model structure for the agent-based simulation of electricity demand. Another important aspect is the provision of a detailed data set. Since electricity prices depend on the demand load, the provision of adequate load profiles is a crucial issue. The necessary timescale can be derived form the development of spot market prices in Germany. An overview of the spot market prices for a selected day in 2006 is given in Figure 5-2. The figure shows that spot market prices vary throughout the day. The difference between market prices from one hour to the next can reach more than 10 Euro/MWh during the selected day. If these variations are taken into account, it seems to be necessary to provide a load profile of electricity demand on hourly level.

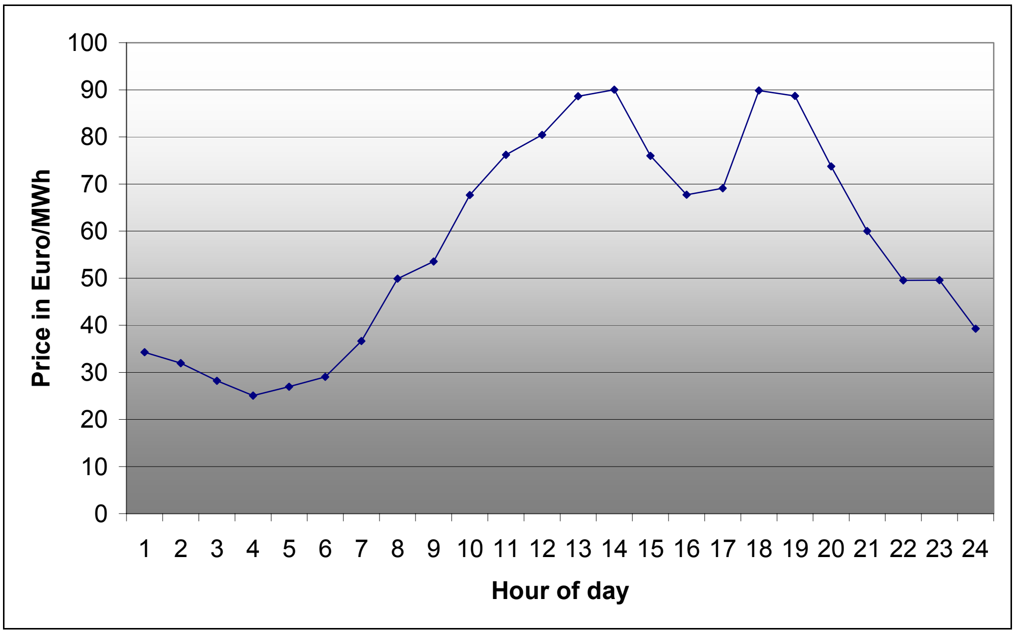

Figure 5-2: German spot market prices for a day in 2006
Source: based on European Energy Exchange [EEX], 2007e

The goal to simulate the electricity sector on an hourly level in an agent-based simulation leads to extensive requirements on the underlying data set. The model requires adequate hourly load profiles for an entire year on the level of a single agent. In addition the sum of the load profiles on that level has to provide an adequate aggregate load profile for the entire German load in order to create realistic prices on the spot market. This section deals with the development of an adequate model structure and the creation and validation of annual hourly load profiles.

5.1.1 Model structure

In the real world the majority of consumers do not buy electricity on the spot market. In principle consumers can buy electricity on several markets, such as the spot market, the future market and via bilateral over the counter trades [OTC]. But the crucial issue is that an own trading department leads to cost of more than 200.000 Euro, which leads to the situation that an own trading department is only feasible for very big consumers (Ellwanger et al., 2000). Therefore most consumers such as households and small enterprises have contracts with electricity suppliers. A similar structure is implemented in the PowerACE simulation platform. Electricity consumption is divided into the four sectors industry, households, services and transport. The development of electricity demand is given in Table 5-1.

Table 5-1: Development of electricity demand by sector

[TWh]	2000	2001	2002	2003	2004	2005	2006
Industry	239.1	240.3	243.1	244.8	249.3	250.5	253.3
Transport	15.9	16.0	16.0	16.1	16.2	16.2	16.3
Services	115.9	117.0	120.6	125.0	126.8	127.3	127.9
Households	130.5	134.4	136.5	139.1	140.4	141.7	142.0
Total	501.4	507.7	516.2	525.0	532.7	535.7	539.5

Source: based on Bundesministerium für Wirtschaft und Technologie [BMWI], 2007a

The electricity demand of these sectors is represented by consumer agents. Consumers are supplied by demand trader agents based on long-term contracts. Since it is not possible to create a single agent for every household or company in Germany, the number of agents has to be reduced to a reasonable amount. In order to solve this issue, agents are created as representatives of a certain type of consumer. A consumer agent is characterized by its own size (size of household, or company size), consumption, load profile and the amount of the total electricity demand it represents. The user can choose the number of consumers per sector or branch involved in the simulation. An overview of the represented branches and technologies is given in the Appendix. In order to ensure that every simulation meets the actual electricity demand, an "Agent-builder" is developed to create every consumer agent and to assign the representative consumption. Based on the consumption data, the "Load Manager" creates and assigns a load profile for each agent. The demand trader purchases the required electricity on the spot market. In the developed simulation platform electricity trades focus on the sport market. This is a simplification of the real world situation where ca. 89 TWh or 16.5 % of the electricity demand were traded on the spot market in 2006 (European Energy Exchange [EEX], 2007f). Other important possibilities for electricity trades are the markets for futures and over the counter trades. A central assumption for this thesis is that the spot market, which has seen increased trading volumes throughout the past year, provides the most important price signal for all electricity trades. In the simulation applied in this thesis the demand trader purchases electricity with a price independent bid. It is assumed that electricity demand is inelastic in the short time horizon of the day-ahead electricity market. This assumption is supported by the fact that price elasticities in the energy sector are low in the short run (see also Wietschel, 1994, p.121 ff.). Currently only very big industrial consumers are aware of the day-ahead projection of spot market prices, which means that large parts of the electricity demand are totally oblivious of hourly spot market prices and therefore inelastic towards hourly prices on the day-ahead market. An overview of the created structure is given in Figure 5-3.

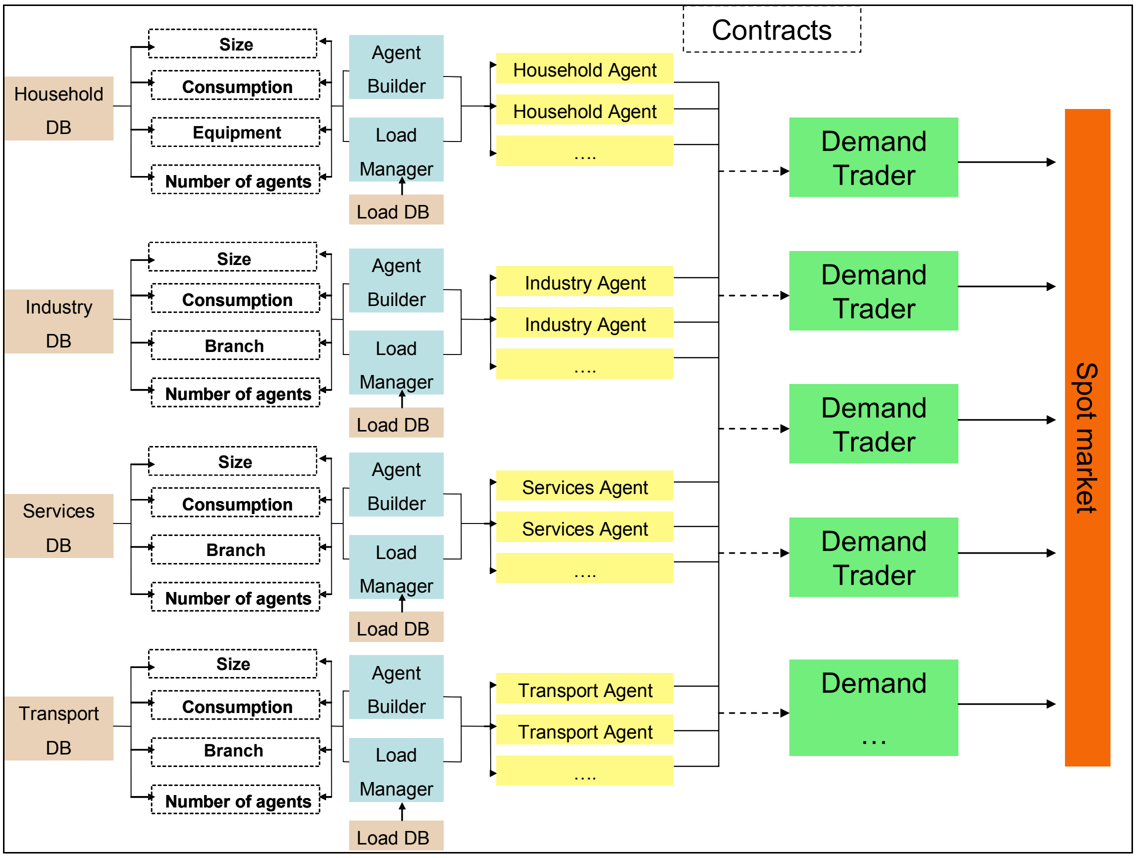

Figure 5-3: Structure of the simulation of electricity demand
Source: own illustration

5.1.2 Calculation of load profiles of electricity demand

As stated at the beginning of this section, the crucial issue for the simulation of electricity demand is the load profile of electricity demand.

In order to create a simulation of the electricity market for an entire year, an hourly load profile for 8760 hours is necessary. The central problem is that such a data set is not available. The German grid operators publish only hourly data for the vertical system load which does not cover the entire demand since it only accounts for upload on the highest voltage grid. Another important source for demand load profiles is the "Union for the Coordination of Transmission of Electricity" [UCTE]. The UCTE publishes the load profile of electricity demand per country. But the data is only available for the third Wednesday of every month. An exception is the year 2000 where data for one Saturday and Sunday per month is available too. It also has to be taken into account that the UCTE does not include consumer generation on lower voltage level. An additional source of data available at the Fraunhofer Institute ISI is a load model which contains a database of load profiles of electricity demand for a number of technologies. These load profiles are available for six typical days: Winter (Weekday, Saturday, Sunday) Summer (Weekday, Saturday, Sunday). These load profiles can be aggregated to create load profiles on the level of branches, sectors or the entire country. Another published load profile is the standard load profile for households (Vattenfall Distribution Hamburg GmbH, 2007). Based on these data sets, the required annual hourly load profile of electricity demand on technology level and country level has to be created. This process is carried out in four steps. The first step is the calibration of the available load profile data on technology level to the published UCTE profiles for the entire country. The next step is the development of an algorithm to create annual hourly profiles on technology level based on the given data set. In a third step the storage heater load profiles are developed and integrated which consider the average daily temperature. In the last step the developed load profiles are validated.

5.1.3 Calibration of the existing data to published load profiles

The first step of the calculation of annual hourly load profiles is the calibration of the ISI load data to the published UCTE data. The monthly UCTE data is aggregated to an hourly profile of a winter day and an hourly profile of a summer day. Thereafter the household load profiles for single technologies are multiplied with the electricity demand and aggregated to a German household profile. In a calibration procedure this profile is compared to the published profile for households (Vattenfall Distribution Hamburg GmbH, 2007). The load profile of the technology category (other) is adjusted until the published profile is met. After the calibration of the household load profile the similar procedure is applied to the aggregated profile for Germany. The load profiles for all technologies are aggregated and compared to the calculated winter and summer profiles (UCTE). In a second procedure the profile of a single technology in the industry sector (others) is adjusted until the model profile meets the UCTE profile.

5.1.4 Calculation of annual load profiles on technology level

After the calibration of the load data set to the published UCTE data the next step is to develop a procedure for the calculation of hourly load profiles for an entire year on technology level and as an aggregate for the entire electricity demand in Germany. The calculation of load profiles on technology level allows to endow every consumer agent with an own load profile which depends on its equipment level of electricity consuming devices. This level of detail allows for a better assessment of the cost of electricity purchases for one consumer and the potential for load management of a single consumer. Therefore the goal is to create realistic annual load profiles on technology level that meet the following requirements. 1. They have to have consistent characteristics. 2. The resulting annual consumption on technology level has to be realistic 3. The published monthly consumption data for Germany has to be met. 4. Minimum and maximum system loads of the system have to be realistic. Based on the limited information, an accurate procedure is not possible. In order to provide a good approximation the following formula has been developed. The first step is to calculate the average annual load profile of each technology for each representative day $l_{a,t,y,h}$. In a second step the difference between the published monthly UCTE data for the representative day $u_{m,y,h}$ and the calculated annual average UCTE load profile is calculated. This step determines the differences between the monthly profiles. In a third step the difference between the seasonal profiles for the UCTE data and the load profiles on technology level is calculated. By dividing the seasonal differences on technology level by the seasonal differences in the aggregate UCTE data and by multiplying the result by the calculated profile of the first step, seasonality is introduced. Load profiles on technology level with no seasonality like many industry profiles are not changed by this calculation. And profiles on technology level with high seasonality are adjusted in relation to the seasonality of the German load profile.

Formula 5-1: Algorithm for the calculation of load profiles on annual level

$$l_{t,m,y,h} = l_{a,t,y,h} + \left(\frac{l_{t,w,y,h} - l_{t,s,y,h}}{u_{w,y,h} - u_{s,y,h}} \right) \cdot \left(u_{m,y,h} - u_{a,m,y,h} \right)$$

Legend:

Variables	Unit	Indices
l = Load	[MW]	a = Annual average
u = UCTE load data	[MW]	h = Hour
		m = Month
		s = Summer average
		t = Technology index
		w = Winter average
		y = Representative day

In rare cases the developed algorithm can lead to load profiles with negative load. Therefore a second procedure is applied which sets the load in these hours to zero.

5.1.5 Integration of storage heaters

Another aspect which is to be taken into account for the creation of realistic load profiles is the integration of the impact of temperatures on the load profile. The load profile that is most affected by temperatures is the profile of storage heaters. Electric storage heaters are applied in the household and the service sector. They play an important role in the shape of the German load profile. Unfortunately no aggregate profile for night storage heaters in Germany is published. But one German grid operator provides profiles for the calculation of the load profile of night storage heaters based on the average daily temperature (EnBW Energie Baden-Württemberg AG, 2007b). These profiles are utilized for the creation of daily night storage profiles. In order to calculate the daily average temperature in Germany, published average daily temperatures for 44 climate stations are utilized (Deutscher Wetterdienst [DWD], 2007). The climate stations are weighted by the approximate population of the region. Based on the weighted data of the climate station, the average daily temperature for Germany is calculated. The calculated load profiles are used to replace the model based data for storage heating in the service sector and the household sector. The calculated load profile of storage heaters in the household sector for the year 2001 is given in Figure 5-4 as an example. The maximum load of almost 20 GW underlines the importance of the profile.

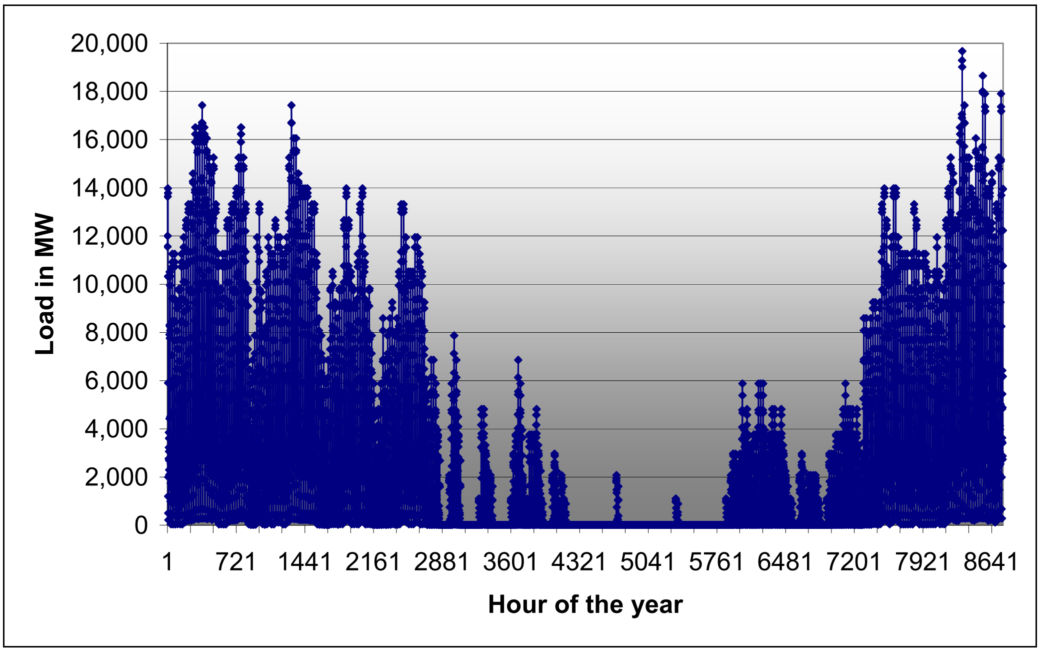

Figure 5-4: Calculated load profile for storage heaters in the household sector 2001

Source: own illustration

An example of the resulting aggregate German load profile for the year 2001 is given in Figure 5-5. The calculated load profiles for Germany are an important basis for the simulation. However, it has to be taken into account that these profiles do not cover the entire electricity demand in Germany as they do not include the electricity demand that is covered by customer generation such as industrial CHP plants or small block heat and power plants since this demand is not part of the measured UCTE data. This segment of electricity demand is included as an aggregate additional profile in the simulation. In a last step the grid losses of 5 % of the electricity demand are integrated. The electricity required to cover the grid losses is purchased by the grid operator in the simulation in accordance with the existing practice.

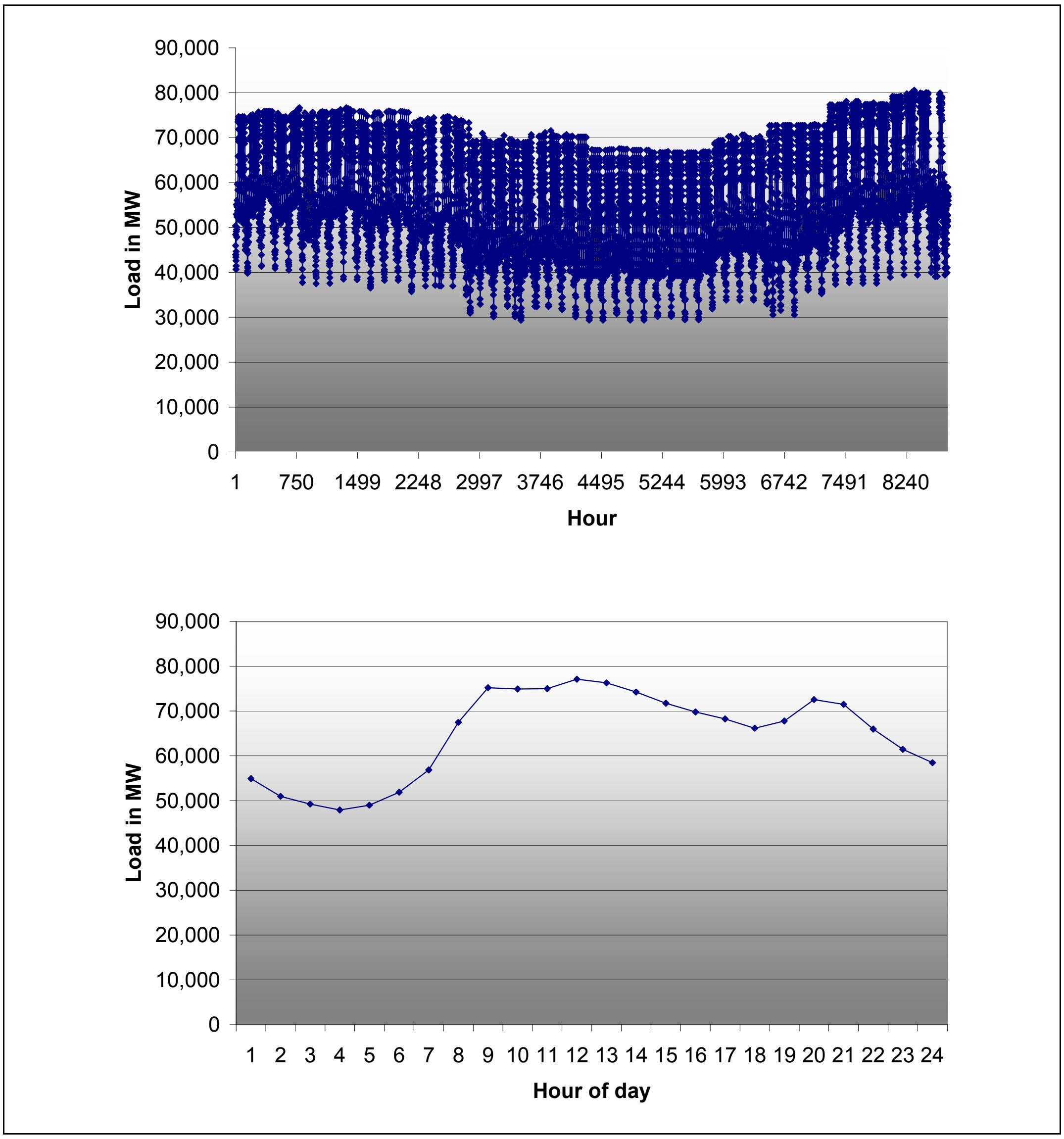

Figure 5-5: Calculated German load profile for the year 2001 and a selected day
Source: own illustration

5.1.6 Evaluation

Since the developed algorithm can only create an approximation of the real world development, a crucial issue is the validation of the created results with regard to the criteria stated above. The first criterion is the comparison of electricity demand. A comparison of the sum of hourly profiles and the published annual electricity demand for the year 2000 on total and on sectoral level shows very low deviations with a maximum of 1.5 % in the industry sector. On technology level the deviation of electricity demand in most cases is below 1 %. This seems to be acceptable. A comparison of the monthly electricity demand is given in Figure 5-6.

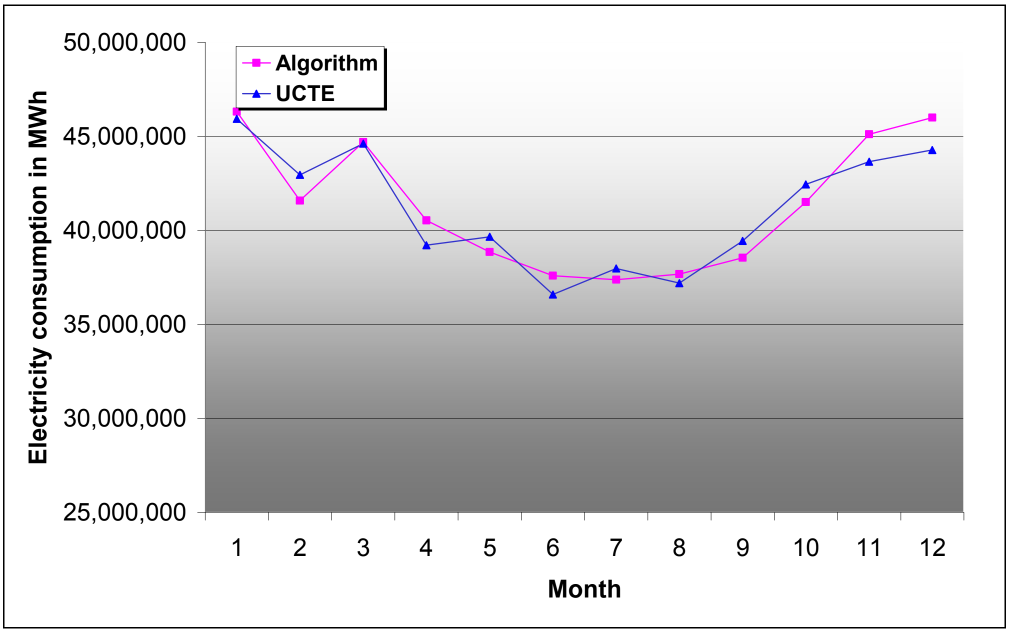

Figure 5-6: Comparison of electricity demand for the year 2001

Source: own illustration

The figure shows that the developed algorithm provides a profile which closely follows tha real world development of the monthly electricity demand. A higher deviation occurs in December with a deviation of 3.8 %. This is mainly caused by the fact that the day for which the UCTE data is available was a day with relatively high load. Since the algorithm is calibrated to this profile, the electricity demand is slightly overestimated. The next comparison is the analysis of minimal load and peak load. In terms of peak load the developed algorithm leads to a slight underestimation of the peak load by 2.3 %. The minimum load is underestimated by 1.8 GW or 5.7 %. If it is taken into account that the UCTE data covers only a limited number of days, which are characterized by their specific weather conditions, the deviations of the developed annual load profile from the published UCTE seem to be acceptable.

Table 5-2: Comparison of extreme load events of the year 2001

	UCTE GW	**Algorithm** GW	**Difference** GW	**Difference** %
Peak load	82.4	80.5	1.9	-2.31
Minimum load	31.0	29.3	1.8	-5.66

Source: UCTE data based on Union for the Co-ordination of Transmission of Electricity [UCTE], 2007

5.2 Simulation of renewable electricity generation

A central goal of this thesis is the analysis of the impact of the supported renewable electricity generation on the electricity sector. Therefore the simulation of renewable electricity generation plays an important role. Similar to the simulation of electricity demand the task of the simulation of renewable electricity generation involves two important tasks. After the development of a model structure for the simulation the necessary data has to be provided. Both issues are discussed in this section.

5.2.1 Model structure

Renewable electricity generation plays a growing role in the German electricity sector. According to the Renewable Energy Sources Act (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2004a) the electricity generated from renewable energy sources has to be bought by grid operators at guaranteed feed-in tariffs. Based on a prognosis of renewable electricity generation, renewable electricity is sold as a base load block to the electricity suppliers. The suppliers have to buy the renewable base load block at the average price of the feed-in tariffs paid for each technology. The amount of electricity that has to be bought that way is determined according to the market share of each supplier. On a day-ahead basis a new prognosis of renewable electricity generation is calculated and the differences between the sold base-load block and the new day-ahead hourly load prognosis have to be levelled out by the grid operators. In many cases the necessary trades are carried out at the spot market (E.ON, 2005). On the actual day of physical delivery differences between the day-ahead prognosis and the updated prognosis of renewable electricity have to be levelled out again. This process can be carried out on the intra-day market or by contracts with generation companies. If differences between prognosis and actual development remain at the time of actual delivery, balance energy has to be purchased by the grid operators. The costs of this service are included in the grid fees.

The simulation of renewable electricity generation in the PowerACE simulation platform is orientated on the real world processes described above. The first step is the creation of renewable agents. The renewable load database contains load profiles, utilization data and the installed capacity for 10 renewable technologies. An overview is given in Table 5-3.

Table 5-3: List of renewable technologies integrated into the simulation

1. Wind onshore	3. Small hydro	5. Biomass	7. Sewage gas	9. Photovoltaics
2. Wind offshore	4. Large hydro	6. Biogas	8. Landfill gas	10. Geothermal

Based on the data stored in the database, the agent builder creates one agent for each renewable technology. The integration of the renewable electricity generation into the electricity market is structured as follows. The renewable agents sell their generated electricity to the agent "Gridoperator Renewables". The grid operator is linked to a support database where the different feed-in tariffs for the German support scheme are stored. The grid operator buys the renewable electricity generation at the given feed-in tariff of each technology. Since renewable electricity generation, especially wind and PV, tends to have a fluctuating character, the integration of renewable load profiles is an important aspect. In the developed simulation platform the projection of load profiles is carried out by the "Load Prognosis Manager." Based on the data stored in the database, the "Load Prognosis Manager" creates a prognosis of the monthly electricity generation. Based on this prognosis, the "Gridoperator Renewables" calculates the monthly base load block of renewable electricity generation that has to be purchased by each demand trader agent at the average feed-in tariff determined by the grid operator. This process is carried out on monthly basis. On daily basis the "Load Prognosis Manager" creates a day-ahead prognosis for the renewable electricity generation on the next day. A prognosis error can be integrated by shifting the actual load profile along the timescale. The formula is given in Formula 5-2.

Formula 5-2: Integration of prognosis errors for renewable electricity generation

$$\lambda(h) = r(h+t)$$

Legend:

Variables			**Unit**	**Indices**
h	=	Hour	[Hour]	
r	=	Actual renewable load	[MW]	
t	=	Delay for the simulation of prognosis errors	[Hour]	
λ	=	Projected renewable load	[MW]	

However, in order to simplify the analysis carried out in this thesis the prognosis error is set to zero if not stated otherwise. Based on the created load prognosis, the agent "Gridoperator Renewables" determines the deviation of the sold base load block from the projected load profile. The resulting load profile of the deviation is passed on to the "Gridoperator Trader" who places the necessary offers and bids as price-independent bids on the spot market. Additional trades on the intra-day market and the purchase of balance energy for the remaining deviations of renewable electricity generation from the available prognosis data are not integrated into the PowerACE simulation platform. The analysis of the cost of these services is carried out without the support of the PowerACE simulation platform. An overview of the developed structure for the simulation of renewable electricity generation is given in Figure 5-7.

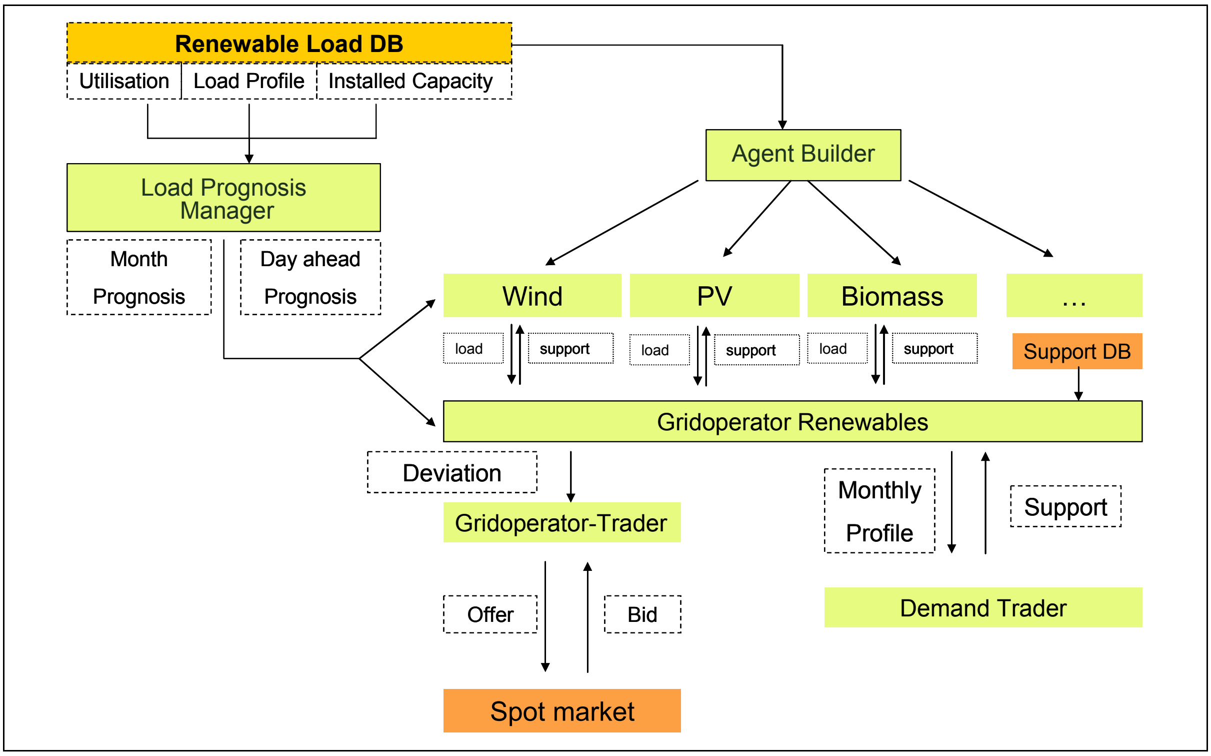

Figure 5-7: Structure of the simulation of renewable electricity generation
Source: own illustration

5.2.2 Provision of load profiles

An important issue for the simulation of renewable electricity generation is the provision of hourly load profiles of renewable electricity generation. The installed capacity of renewable electricity generation in Germany of the year 2006 presented in Figure 5-8 underlines the importance of renewable electricity generation.

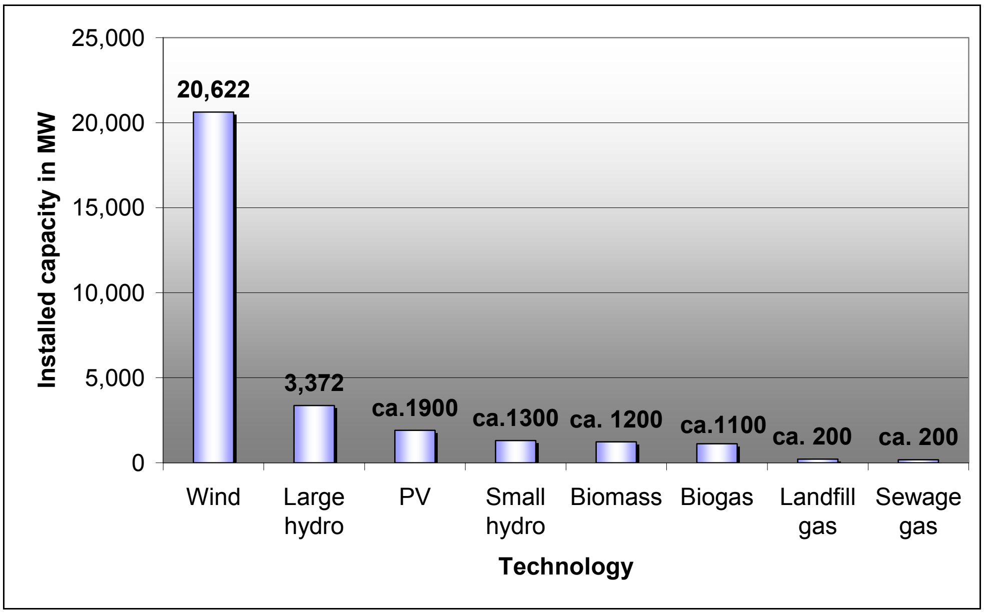

Figure 5-8: Installed capacities of renewable technologies in Germany in the year 2006

Sources: Deutsches Windenergie Institut [DEWI], 2007; own calculations based on Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2007a)

Due to the high installed capacity and the fluctuating character of the load profile of wind energy is an important aspect in the electricity sector. Despite the importance of wind energy it took some time until the load profile of wind energy was published by the grid operators. Therefore the ISI-Wind model (Sensfuß et al., 2003) has been developed which uses extensive meteorological data (wind speed, temperatures) and assumptions on the type and regional distribution of wind turbines for the calculation of an hourly load profile of wind energy in Germany. Based on the meteorological data set, the model provides hourly load profiles of wind energy for the years 1990, 1995 and 1996 representing good, medium and bad wind conditions. An extended version of the ISI-Wind model applies a more detailed commercial data set of the DWD Miriam network (Deutscher Wetterdienst [DWD], 2007) to generate load profiles for the years 1998, 2000 and 2001 on an even shorter timescale of 10 minutes. Since many of the analysises carried out in this thesis deal with the analysis of spot market prices in later years, additional data is necessary. For the years 2004 and 2005 commercial hourly wind profiles of the ISET SEPCAMO model (Institut für Solare Energieversorgungstechnik [ISET], 2007a) have been purchased. An official profile of electricity generation by wind energy published by the German Association of Grid operators [VDN] is available for the year 2006. An overview of the data sets applied in the PowerACE simulation and the relative wind conditions of the selected years is given in Table 5-4.

Table 5-4: Applied data sets for the electricity generation of wind energy

Year	Meterological Data	Electricity Generation	Windindex* (%)
1990	DWD	ISI-Wind	114
1995	DWD	ISI-Wind	106
1996	DWD	ISI-Wind	88
1998	DWD	ISI-Wind-Extended	110
2000	DWD	ISI-Wind-Extended	102
2001	DWD	ISI-Wind-Extended	94
2004	none	ISET-Sepcamo	98
2005	none	ISET-Sepcamo	89
2006	none	VDN-Data	90

Sources: * Windindex: Institut für Solare Energieversorgungstechnik [ISET], 2007b;Internationales Wirtschaftsforum Regenerative Energien [IWR], 2002; VDN-data: Verband der Netzbetreiber [VDN], 2007c)

In case of PV an hourly profile created by the ISI-PV model is applied. The model uses published data on solar radiation to create a load curve of PV (for more details see (Sensfuß, 2003). Due to the lower importance the underlying meteorological data set is not changed for the different years. The load profile is normalized to an annual generation of 1 MWh and scaled up by the installed capacity and an average utilization of PV in terms of full load hours. A similar procedure is applied to the load profiles of other renewable technologies. In case of hydro power plants a load profile published by Wiese is applied (Wiese, 1994). It is normalized to an annual generation of 1 MWh per year. For the upscaling different utilizations in terms of full load hours are applied for large and small hydro power plants. In case of biomass power plants and the other bio-fuel based technologies information is rather scarce. Therefore an aggregate profile for CHP plants is used since it is assumed that many biomass plants run as CHP plants to qualify for a higher feed-in tariff. Again different rates of utilization are applied to the different technologies. As an example for the created load profiles the aggregate load profile of renewable electricity generation for the year 2006 is given in Figure 5-9.

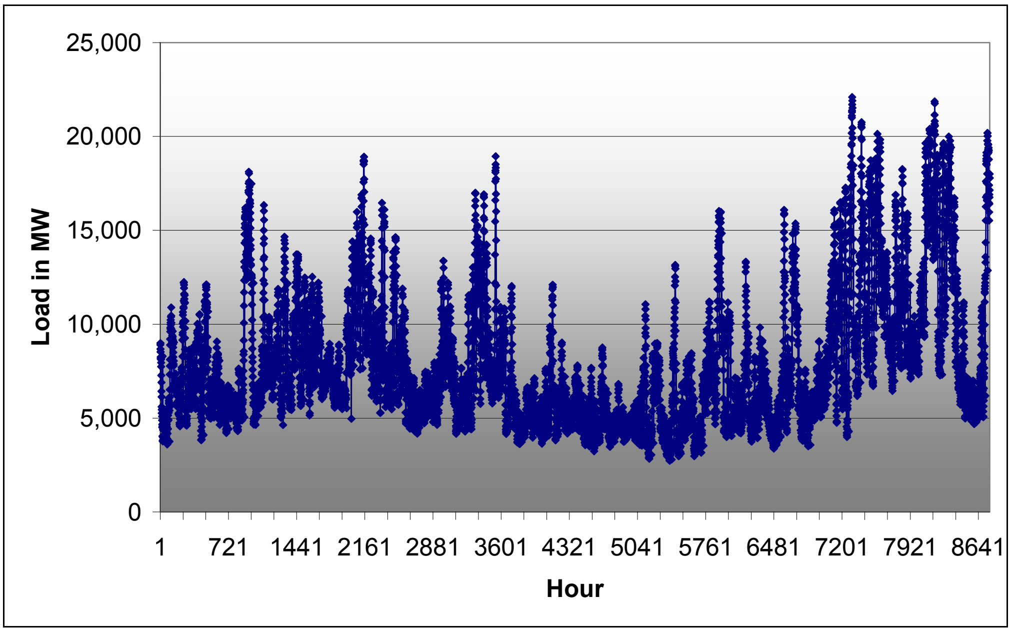

Figure 5-9: Developed load profile of renewable electricity generation for the year 2006
Source: own illustration

5.3 Simulation of electricity supply

The representation of electricity supply is an important part of the simulation of the electricity markets. The central tasks for the development of the agent–based simulation platform are the development of an adequate model structure for the provision of an adequate data set and the development of an algorithm for the creation of a bid price for the power plants. The module of the electricity supply side is a slightly modified version of the supply module which was developed by Massimo Genoese at the Institute of Industrial Production at the University Karlsruhe (see also Genoese et al., 2006; Genoese et al., 2005; Sensfuß et al., 2007b). After a short description of the agent structure the input data set is described. In the last parts of this section the developed bidding algorithm is presented.

5.3.1 Model structure

The agent-based simulation of the electricity supply is orientated on the real situation. Five major production companies (EnBW, Eon, RWE, Vattenfall Europe, Steag) are modelled as separate players. Industrial electricity generation is represented by a single player. All other production units of smaller companies are represented by an additional player. Due to the complexity of the issues related with electricity supply a single player is represented by several agents. The generator agent manages the power plant portfolio. It determines the available capacity of every plant and determines the fundamental bid price for every power plant. Based on the data provided by the generator agents, the trader agents for the spot market, the balancing market and an experimental CO_2 market, which is not utilized in this thesis, can trade on their markets. The traders place bids on the markets and evaluate the market results.

5.3.2 Fuel prices

A central input factor for the calculation of the variable cost of power plants is the fuel price. The prices of different fuels are stored in a fuel price database. The management of fuel prices is carried out by the "Fuel-Price-Management". The user can choose between different fuel price scenarios. Depending on the fuel prices are available on monthly, quarterly and annual level. For the period 2000-2006 historical prices are available as published import prices. In order to calculate the fuel prices for power plants, transport premiums are added to the price. In case of fuel for nuclear power plants (Uranium) no transport cost are assumed since they are part of the fuel cycle cost. A similar situation occurs for lignite power plants which are built close to mines.

Table 5-5: Available data on fuel prices

Fuel	Prices			Transport
	annual	**quaterly**	**monthly**	**Euro/MWh**
Lignite	available	–	–	0.0
Uranium	available	available	available	0.0
Hard coal	available	available	–	0.4
Gas	available	available	available	0.3
Oil	available	available	available	0.3

Sources: Own assumptions based on: Enzensberger, 2003; WINGAS TRANSPORT, 2007

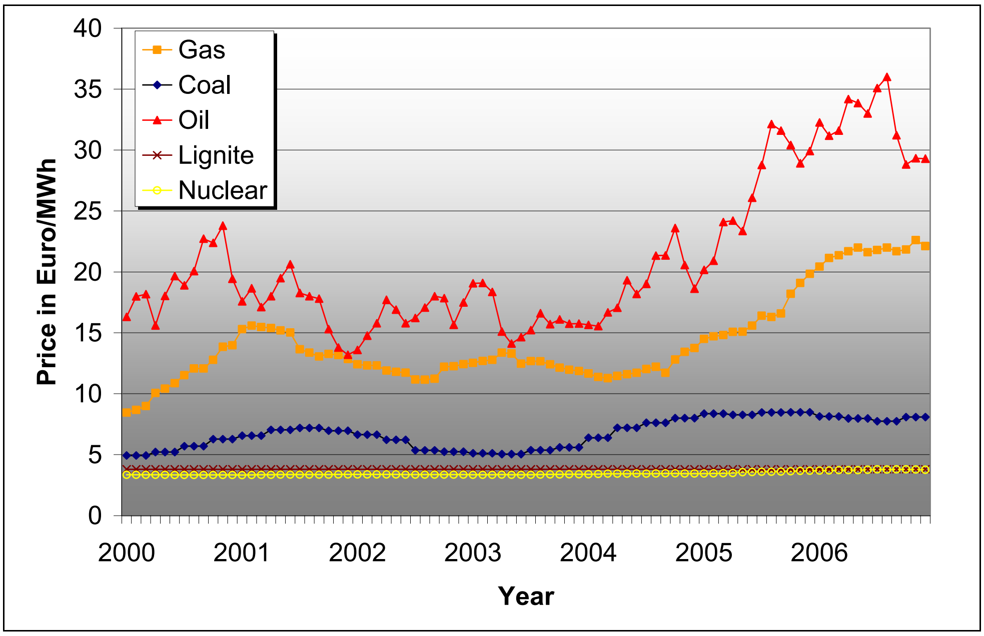

Figure 5-10: Development of fuel prices for power plants

Sources: Uranium: The Ux Consulting Company, 2007 own calculations based on Kugeler and Lucas, 2007; Gas: Bundesministerium für Wirtschaft und Technologie [BMWI], 2007b; Oil: Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2007b; Coal: Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2007a;Transport cost: Enzensberger, 2003, p.102

5.3.3 CO_2 prices

As described in Chapter 2 the European Emission Trading scheme started in 2005. With the beginning of emission trading the price of CO_2 emission rights becomes an input factor which has to be taken into account for the calculation of production cost. In the simulations applied for this thesis CO_2 prices are treated as exogenous input factor. The user can choose a constant CO_2 price for an entire year or create time series of daily prices which are stored in the CO_2 price database. In the basic setup the simulation platform is based on daily CO_2 prices published by the EEX (see Figure 5-11). The prices for days without emission trading such as Sundays are determined by linear interpolation.

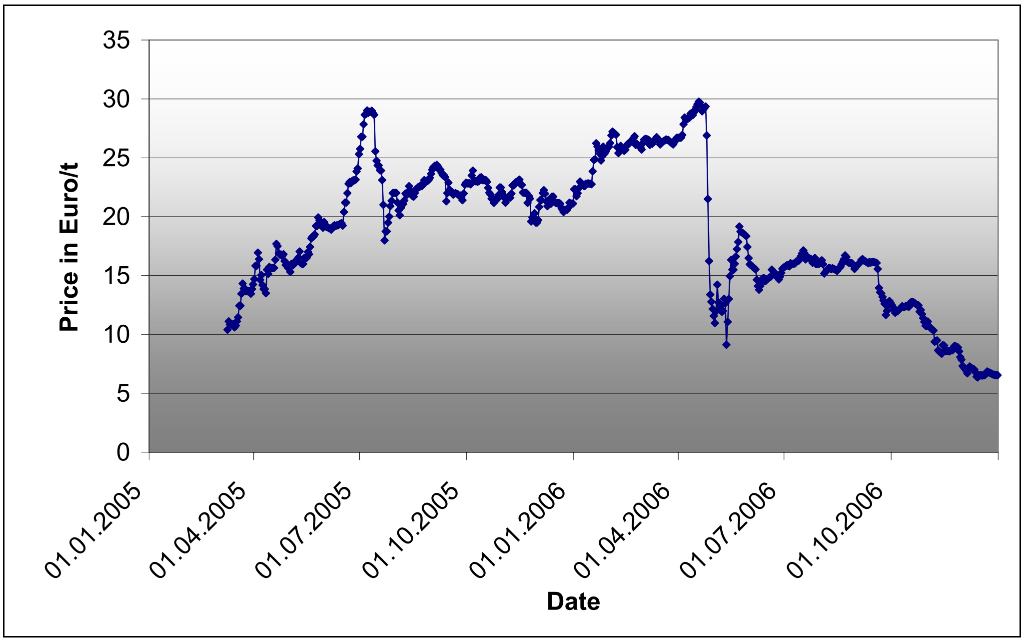

Figure 5-11: Prices for CO_2 emission allowances [EUA] in the period 2005-2006

Sources: European Energy Exchange [EEX], 2007a; European Energy Exchange [EEX], 2007b

5.3.4 Export/Import

Since PowerACE focuses on Germany only, imports and exports of electricity have to be integrated as external input into the simulation. This external input is provided by the PERSEUS linear optimization model (see also Enzensberger, 2003; Möst et al., 2005), a European energy system model where Germany and all border countries are modelled. In view of the transmission capacities, costs, electricity demand and supply, export/import flows between these countries are computed and used as a fixed load flow for the PowerACE model runs. The resulting seasonal profiles are presented in Figure 5-12. Imports are displayed with positive sign. Since only one profile is available, it is assumed that the profile is constant for the analysed period.

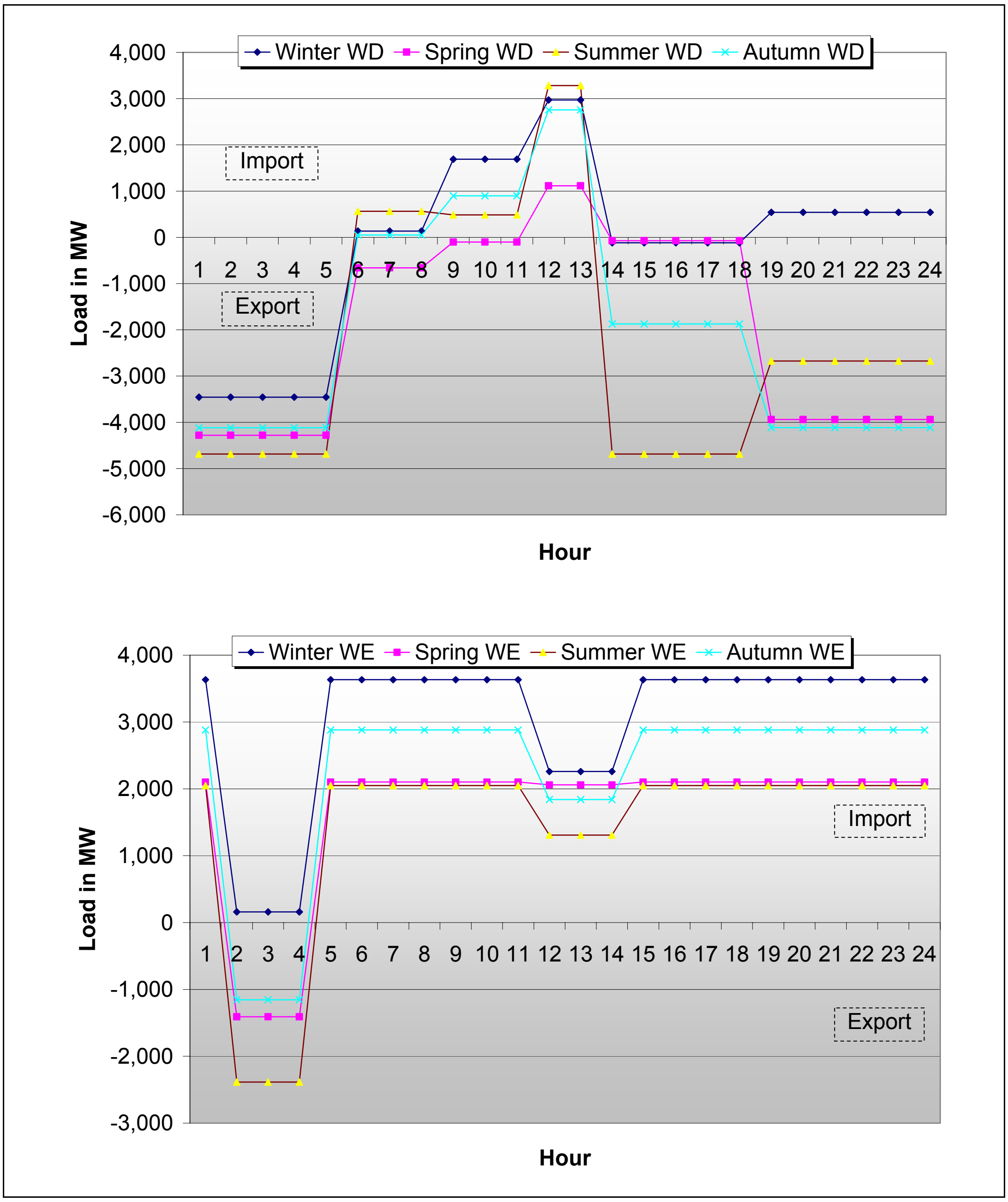

Figure 5-12: Load Profiles for electricity export and import in Germany
Source: own illustration

5.3.5 Power plant database

The most important data set on the supply side is the power plant database. The database is provided by the Institute for Industrial Production at the University Karlsruhe. The power plant database contains detailed data of more than 1200 power plants in Germany. Important characteristics stored in the database are installed capacity, efficiency, type of fuel, year of construction and ownership. In order to reduce the calculation time of the simulation conventional power plants with an installed capacity below 5 MW are excluded from the simulation. An example of the aggregated merit-order curve (available plants sorted according to their variable cost) on a selected day in the year 2004 is given in Figure 5-13.

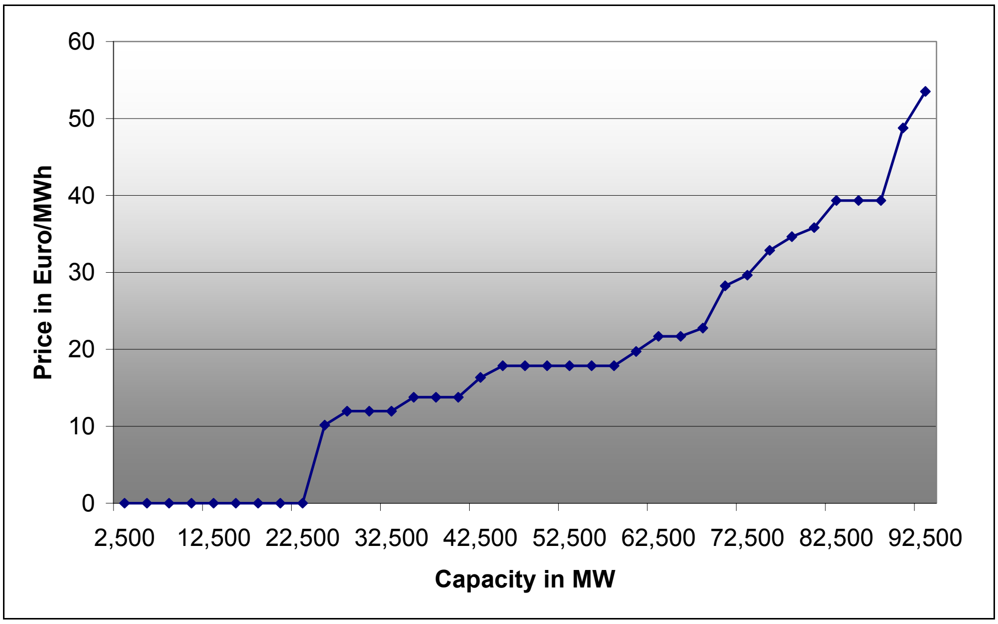

Figure 5-13: Merit-order curve for a selected day in 2004
Source: own illustration

5.3.6 Price prognosis

Each supply trader agent creates a price prognosis for the next day which is based on perfect knowledge of the variable cost and generation capacity of all plants. It is important to note that each supply trader agent cannot know exactly which plant will be subject to unforeseen outages on the next day. The power plants are sorted according to their variable generation cost and capacity. The last plant necessary to satisfy demand determines the projected price. An overview of the applied algorithm is given in Formula 5-4.

Formula 5-3: Creation of a price prognosis

1. Collection of sorted plants

$$M = \{g_1, ..., g_v\}$$

2. Points in the merit-order curve

$$m_{i,h} = \{c_{i,h}, g_{i,h}\}$$

2. Calculation of the variable cost

$$c_{i,h} = \frac{p_{f,i}}{\eta_i} + \frac{z \cdot e_i \cdot \zeta_i}{\eta_i} + o_i$$

3. Sorting criteria

3 a) $c_{i+1,h} > c_{i,h}$

3 b) $(|g_{i+1,h}| \le |g_{i,h}|)$ *if* $(c_{i+1,h} = c_{i,h})$

4. Price prediction for hour h

$$\varphi_h = min\left\{ c_{i,h} \quad if \quad \sum_{i=1}^{j} v_{i,h} \le 0 \right\}$$

Legend:

Variables	**Unit**	**Indices**
c = Variable cost	[Euro/MWh]	f = Fuel
e = CO_2-emission factor	[t CO_2/MWh]	h = Hour
g = Capacity of power plant	[MW]	i = Power plant
M = Collection of all sorted plants	[None]	j = Marginal plant
l = Load	[MW]	ν = Number of plants
m = Point of the merit-order curve	[None]	
o = Variable operation and maintenance cost	[Euro/MWh]	
p = Price	[Euro/MWh]	
z = CO_2 price	[Euro/t]	
ζ = CO_2 price integration factor of fuel	[None]	
η = Efficiency	[%]	
φ = Predicted price of spot market	[Euro/MWh]	

5.3.7 Calculation of the bid price for plants

A central part of the simulation of the electricity market is the creation of the bid price for power plants. The algorithm developed for the PowerACE simulation platform is mainly based on variable cost. Electricity generation companies bid their merit-order curves based on the variable electricity generation cost of their power plants. An additional algorithm is used for the integration of start-up cost into the bid price. In case of base load power plants the opportunity costs of a potential restart of the power plant are used to lower the bid price in hours where the price projection of the agent assumes that the plant is not scheduled. An exception are nuclear power plants. Due to the costly permission procedure in the case of a restart of a nuclear power plant it is assumed that nuclear plants are kept running whenever possible. In order to integrate this aspect a bid price of zero is assumed for nuclear power plants. The calculation of the price prognosis itself is shown in Chapter 5.3.6. For oil and gas fired units the start-up costs are added to the bid price for the hours when the plants are expected to be in operation (see Formula 5-4 for details).

Formula 5-4: Calculation of the bid price for power plants (see also Sensfuß and Genoese, 2006)

$$p_{i,h} = \begin{cases} max(\frac{p_{f,i}}{\eta_i} + \frac{z \cdot e_f \cdot \zeta_f}{\eta_i} + o_i - \frac{s_i}{\upsilon}, 0) & if\ \varphi_h < \left(\frac{p_{f,i}}{\eta_i} + \frac{z \cdot e_f \cdot \zeta_f}{\eta_i} + o_i \right)\ and\ i \in G \\ \frac{p_{f,i}}{\eta_i} + \frac{z \cdot e_f \cdot \zeta_f}{\eta_i}_{f} + o_i + \frac{s_i}{\sigma} & if\ \varphi_h > \left(\frac{p_{f,i}}{\eta_i} + \frac{z \cdot e_f \cdot \zeta_f}{\eta_i} + o_i \right)\ and\ i \in P \\ \frac{p_{f,i}}{\eta_i} + \frac{z \cdot e_f \cdot \zeta_f}{\eta_i} + o_i & otherwise \end{cases}$$

$$i \in M\ ; G \subset M\ ; P \subset M\ ; G \cap P = \emptyset$$

Legend:

Variables			**Unit**	**Indices**		
e	=	CO_2-emission factor	[t CO_2/MWh]	f	=	Fuel
G	=	Set of base load power plants	[None]	h	=	Hour
M	=	Set of all operation-ready power plants	[None]	i	=	Plant
o	=	Variable operation and maintenance cost	[Euro/MWh]			
P	=	Set of peak load power plants	[None]			
p	=	Price	[Euro/MWh]			
s	=	Start-up cost of plant	[Euro]			
z	=	CO_2 price	[Euro/t]			
η	=	Efficiency	[%]			
σ	=	Number of scheduled hours per day	[Hour]			
υ	=	Number of unscheduled hours per day	[Hour]			
φ	=	Predicted price of spot market	[Euro/MWh]			
ζ	=	CO_2 price integration factor	[None]			

Another important aspect of the generation of market prices is the availability of power plants. Thereby a different procedure is applied to scheduled and unscheduled outages of power plants. In the case of nuclear power plants the availability is based on the published energy production of nuclear power plants (Union for the Co-ordination of Transmission of Electricity [UCTE], 2006). The available capacity is determined accordingly in a deterministic way. In order to integrate all other power plants a random generator is used. The availability of power plants is determined by a generated set of uniform distributed random numbers between 0 and 100 %. If the drawn number exceeds the average availability of the given plant, the available capacity for the given plant is set to zero (Formula 5-5). Thereby the availability is determined on daily level for every single plant. This leads to the fact that the supply curve changes every day. Since the case study seeks to analyse the structural effect of renewable electricity generation on market prices, simulation runs have to be repeated in order to level out this effect.

In a calibration procedure the average availability of fossil fuel fired power plants on weekdays is set to 98 %. A crucial issue is the availability of power plants on weekends. The available information on power plant dispatch and market prices indicates that scheduled maintenance work is preferably scheduled at weekends due to the lower demand and the lower market prices. Since details on the dispatch of power plants at weekends are unknown, the average utilization of fossil fired power plants is set to *93 %* based on a calibration procedure.

Formula 5-5: Calculation of the available capacity of a plant

$$\gamma = \begin{cases} g & \text{if } r < a_i \\ 0 & \text{otherwise} \end{cases}$$

Legend:

Variables			**Unit**	**Indices**
a	=	Average availability of plant	[%]	i = Plant
γ	=	Available capacity of power plant	[MW]	
g	=	Maximum capacity of power plant	[MW]	
r	=	Uniform distributed random variable	[None]	

Since market prices in the year 2005 tend to be very high in the peak load segment, an additional mark-up is added to the bid price depending on the expected ratio of load to be covered and available generation capacity. The mark-up is meant as an integration of the fixed cost of power plants depending on the scarcity of generation capacity. An overview is given in Formula 5-6 and Figure 5-14.

Formula 5-6: Scarcity mark-up for the year 2005 (added to bid price) (for more details see Genoese et al., 2006)

1. Calculation of the scarcity factor

$$s^* = \frac{\gamma}{l_h - r_h}$$

2. Definition of the lower bound

$$u = 2;$$

3. Collection the scarcity steps

$$X = \{b_1, ..., b_v\} = \{2,\ 1.8,\ 1.2,\ 1\}$$

4. Calculation of the mark-up

$$\mu_h = \begin{cases} 0 & \text{if} \quad s^* < u \\ \mu_i & \text{if} \quad b_{i-1} \le s^* \le b_i \end{cases}$$

5. Mark-up is added to the bid price

$$p_h^* = p_h + \mu_h$$

Legend:

Variables			Unit	Indices		
b	=	Bound of scarcity step	[None]	h	=	Hour
l	=	Load	[MW]	i	=	Scarcity step
p	=	Bid price	[Euro/MWh]	v	=	Number of steps
p*	=	Adjusted bid price	[Euro/MWh]			
r	=	Projected renewable generation	[MW]			
s*	=	Scarcity factor	[None]			
u	=	Lower bound	[None]			
X	=	Collection of scarcity steps	[None]			
γ	=	Available generation capacity	[MW]			
μ	=	Mark-up	[Euro/MWh]			

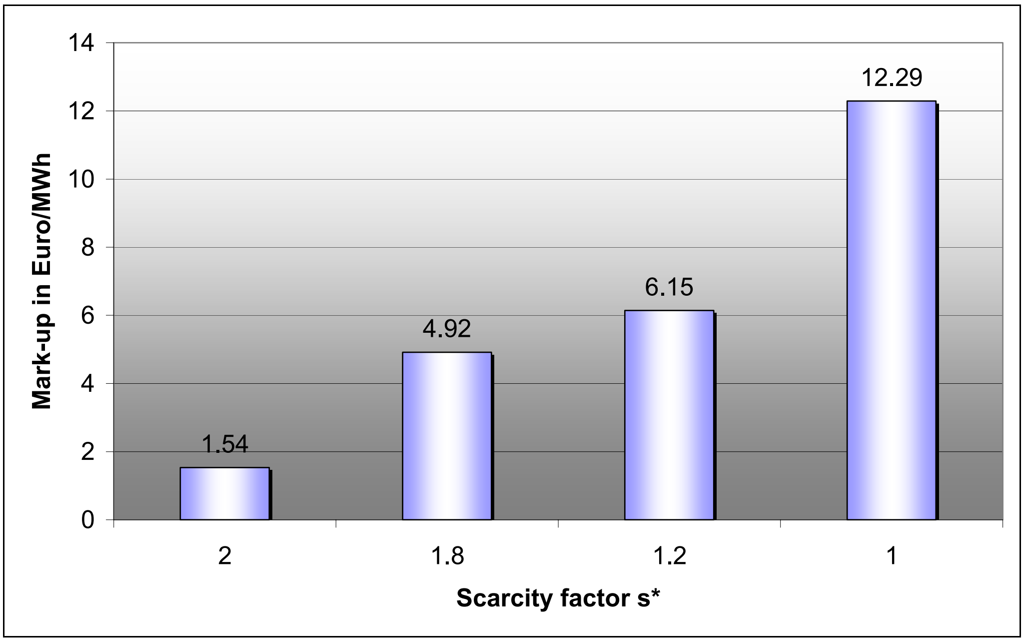

Figure 5-14: Scarcity mark-up
Source: own illustration

5.4 Simulation of electricity markets

5.4.1 Spot market

The central market within the PowerACE simulation platform is the spot market for electricity. The entire German electricity generation and demand are traded on the spot market on an hourly basis. The spot market is executed every day as a day-ahead market. The market operator collects all bids and determines the market clearing price for every hour. All bids for a given hour h are collected and sorted according to the price.

Formula 5-7: Sorting of bids

1. Definition of bid

$$b_{i,h} = \{p_{i,h}, v_{i,h}\}$$

2. Supply: Volume is negative

$$v < 0$$

3. Demand: Volume is positive

$$v > 0$$

3. Collection of bids

$$B_h = \{b_{1,h}, ..., b_{m,h}\}$$

4. Sorting criteria

a) $p_{i+1,h} > p_{i,h}$

b) $(|v_{i+1,h}| \leq |v_{i,h}|) \;\; if \;\; (p_{i+1,h} = p_{i,h})$

Legend:

Variables			Unit	Indices		
B	=	Collection of all sorted bids	[None]	h	=	Hour
b	=	Single bid	[None]	i	=	Index of bid
p	=	Price of bid	[Euro/MWh]	m	=	Number of bids
v	=	Volume of bid	[MW]			

In a next step the aggregate supply curve is calculated by the market operator.

Formula 5-8: Calculation of the aggregated supply curve

$$p(l_h)=\min_{B_h}\left\{\left\{\begin{array}{ll} max(\frac{p_{f,i}}{\eta_i}+\frac{z\cdot e_f\cdot\zeta_f}{\eta_i}+o_i-\frac{s_i}{\upsilon},0) & if\ \varphi_h<\left(\frac{p_{f,i}}{\eta_i}+\frac{z\cdot e_f\cdot\zeta_f}{\eta_i}+o_i\right)\wedge i\in G \\ \frac{p_{f,i}}{\eta_i}+\frac{z\cdot e_f\cdot\zeta_f}{\eta_i}+o_i+\frac{s_i}{\sigma} & if\ \varphi_h>\left(\frac{p_{f,i}}{\eta_i}+\frac{z\cdot e_f\cdot\zeta_f}{\eta_i}+o_i\right)\wedge i\in P \\ \frac{p_{f,i}}{\eta_i}+\frac{z\cdot e_f\cdot\zeta_f}{\eta_i}+o_i & otherwise \end{array}\right\} if\ \sum_1^{j-1}v_i<l_h\le\sum_1^{j}v_i\right\}$$

$j\in\aleph;$ power plants $i\in M; G\subset M; P\subset M; G\cap P=\varnothing$

Legend:

Variables			**Unit**	**Indices**		
B	=	Collection of bids	[None]	f	=	Fuel
e	=	CO_2-emission factor	[t CO_2/MWh]	h	=	Hour
G	=	Set of base load power plants	[None]	i	=	Plant
l	=	Load	[MW]	j	=	Bid
M	=	Set of all operation-ready power plants	[None]			
o	=	Variable operation and maintenance	[Euro/MWh]			
P	=	Set of peak load power plants	[None]			
p	=	Price	[Euro/MWh]			
s	=	Start-up cost of plant	[Euro]			
v	=	Volume of bid	[MW]			
z	=	CO_2 price	[Euro/t]			
η	=	Efficiency	[%]			
σ	=	Number of scheduled hours per day	[Hour]			
υ	=	Number of unscheduled hours per day	[Hour]			
φ	=	Predicted price of spot market	[Euro/MWh			
ζ	=	CO_2 price integration factor	[None]			

Supply and demand are matched by adding up all volumes until zero is crossed. In a slight deviation from the German spot market the EEX market clearing price is determined by the last unit necessary to satisfy the demand. The traded volume is determined as the sum of all demand bids which are satisfied at the market clearing price.

Formula 5-9: Market clearing

1. Determine the bid that balances demand and supply (bids are sorted)

$$p_h^* = \min\left\{ p_{i,h} \quad if \quad \sum_{i=1}^{j} v_{i,h} \leq 0 \right\}$$

2. Definition of marginal bid

$$Definition : i(p_h^*) := i^*$$

3. Calculation of the volume of the last executed bid

$$v_{i^*,h} = v_{i^*,h} + \sum_{i=1}^{i=i^*-1} v_{i,h}$$

3. Calculation of the traded volume

$$v_h^* = -\left(v_{i^*,h} + \sum_{i=1}^{i=i^*} \begin{cases} 0 & if\ v_{i,h} > 0 \\ v_{i,h} & if\ v_{i,h} < 0 \end{cases} \right)$$

Legend:

Variables			Unit	Indices		
B	=	Collection of bids	[None]	h	=	Hour
p*	=	Market clearing price	[Euro/MWh]	i*	=	Index of bid
p	=	Price of bid	[Euro/MWh]	I*	=	Marginal bid
v*	=	Traded volume at the market clearing price	[MWh]	j	=	Marginal bid
v	=	Volume of bid	[MWh]			

5.4.2 Reserve markets

The operation of the transmission networks and the responsibility for the stability of the electricity system in Germany are the task of the transmission system operators. Germany is divided into four zones. The transmission system of each zone is operated by one transmission system operator. In order to ensure system stability, reserve capacity for the provision of system services is necessary. In Germany three types of reserve capacity are used for the provision of system services: Primary reserve, secondary reserve and minute reserve. In 2006 the total reserve capacity amounts to a negative reserve of 5.3 GW and a positive reserve of 7.3 GW. As this capacity reaches a considerable volume which is not available at the spot market for electricity, the reserve markets have to be taken into account for the analysis of the impact of renewable electricity generation. The next sections describe the real world markets for these reserve capacities and the way these markets are modelled in PowerACE.

5.4.2.1 Primary reserve

5.4.2.1.1 Description

The primary reserve or spinning reserve is the first reserve used to stabilize the electricity system. Primary reserve has to be capable to operate at full capacity within 0-30 seconds. It is used for time periods below 15 minutes. This reserve is mostly carried out by power plants which are already in operation. It is activated automatically. The primary reserve market in Germany is organized as a tender for every transmission zone. The capacity is contracted several months ahead for a period of several months. The total capacity in the primary reserve market in 2006 was 656 MW. In order to take part in this market a number of technical qualifications is necessary. Due to these demanding criteria only very few players take part in the primary reserve market. In the Eon transmission zone only 4 players take part (Türkucar, 2006). Primary reserve is paid for by a capacity price only.

An overview of the tenders and market results for the German primary reserve is given in Table 5-6. In order to compare the different markets the market prices are normalized to a daily capacity premium. The approximate market volume for the entire year 2006 was ca. 85 million Euro.

Table 5-6: Overview of key indicators for the primary reserve market

	Unit	RWE	E.ON	Vattenfall	EnBW	Sum
Begin	Date	01/02/2006	01/12/2005	01/09/2005	01/02/2006	
End	Date	30/06/2006	31/05/2006	28/02/2006	30/06/2006	
Length of period	Days	150	182	181	150	
Positive/negative capacity	MW	285	163	137	71	656
Average capacity price	€/MW	54,780	62,860	62,000	51,570	
Marginal capacity price	€/MW	56,200	65,400	62,000	53,300	
Calculated capacity price	€/MW	365	345	343	344	
~Annual market volume for capacity	€	37,989,930	20,548,658	17,128,785	8,909,577	**84,576,949**

Sources: RWE Transportnetz Strom, 2006; E.ON Netz, 2006; Vattenfall Europe Transmission, 2006, EnBW Transportnetze AG, 2006; own calculations

5.4.2.1.2 Simulation of the primary reserve market

Since the necessary amount of primary reserve has not been influenced by renewable energy so far, the main reason for the integration of the primary reserve market is the fact that primary reserve is not available on other electricity markets. This loss of capacity can have an impact on market prices. In order to simplify the simulation Germany is treated as one transmission zone. The primary reserve market is executed once per year. The Grid operator places a price-independent ask for 656 MW of reserve capacity. The supply of primary reserve is implemented by a primary reserve trader for every supply company involved in the simulation. In order to account for the fact that primary reserve is a spinning reserve, only nuclear and lignite plants with a capacity above 30 MW are allowed to bid on the market as these plants are most likely to be used in the base load. Since the requirement of running below full capacity leads to losses in the efficiency of a plant, the simulation is simplified by the fact that power plants are only allowed to bid 5 % of their net capacity on the reserve market. This assumption helps to avoid a complex integration of partial load efficiencies and their impact on the bidding process. In order to determine the bid price for the plants, every reserve bidder creates an hourly price prognosis for the entire period (one year). The prognosis applies the same procedure as the day-ahead prognosis described in Formula 5-10.

Formula 5-10: Calculation of the bid price for a plant on the primary reserve market

$$b = \frac{\sum_{1}^{\iota} \begin{cases} 0 & if \quad c_h > \varphi_h \\ (\varphi_h - c_h) \cdot g & if \quad c_h \le \varphi_h \end{cases}}{g \cdot n}$$

Legend:

Variables			Unit	Indices
b	=	bid price reserve market	[Euro/ (MW Day)]	h = Hour
c	=	Variable cost of plant	[Euro/MWh]	
g	=	Generation capacity	[MW]	
ι	=	Number of hours per year	[None]	
n	=	Length of period	[Days]	
φ	=	Predicted clearing price of spot market	[Euro/MWh]	

The potential income for every plant in the analysed period is calculated by subtracting the variable cost for every plant from the expected market price for every hour where the market price is above the variable cost. Based on this potential profit, an average daily capacity price is calculated for the period. This price is bidden into the reserve market. The reserve market operator collects all bids and sorts the bids according to their capacity price. In order to simplify the simulation the market price is determined as a uniform market clearing price. The last bid necessary to satisfy demand determines the market price for all bids. Although real world markets are implemented as pay as bid price market, results are not likely to deviate too much from uniform market clearing if the participants have a good guess on the likely market price.

5.4.2.2 Secondary reserve market

5.4.2.2.1 Description

Secondary reserve replaces primary reserve. It has to be at full capacity within a period of 30-300 seconds. The use of secondary reserve is also determined automatically. Similar to the primary reserve a tender for several months is used by the grid operators for the purchase of this system service. Again the technical restrictions on this reserve limit the number of players in this market.

Table 5-7: Overview of key indicators for the secondary reserve market

	Unit	RWE	E.ON	Vattenfall	EnBW	Sum
Begin	Date	01/02/2006	01/12/2005	01/09/2005	01/02/2006	
End	Date	30/06/2006	31/05/2006	28/02/2006	30/06/2006	
Length of period	Days	150	182	181	150	
Positive capacity	MW	1,230	800	580	720	3,330
Negative capacity	MW	1,230	400	580	390	2,600
Average positive capacity price	€/MW	41,680	38,270	47,220	39,700	
Max. positive work price	€/MW	111	99	95	139	
Average negative capacity price	€/MW	10,690	11,900	16,000	21,070	
Max. negative work price	€/MW	0	8	1.2	15	
Calculated daily positive capacity price	€/MW	278	210	261	265	
Calculated daily negative capacity price	€/MW	71	65	88	140	
~Annual market volume f. capacity	€	156,743,410	70,946,374	73,942,950	89,549,830	**391,182,564**

Sources: RWE Transportnetz Strom, 2006; E.ON Netz, 2006; Vattenfall Europe Transmission, 2006; EnBW Transportnetze AG, 2006; own calculations

In contrast to the primary reserve market a capacity and a work price are paid for secondary reserve. Another difference is the amount of capacity purchased by the grid operators. The total secondary reserve capacity purchased for Germany in spring 2006 amounts to 2.6 GW negative reserve and 3.3 GW positive reserve. The approximate market volume in terms of capacity prices was 391 million Euro for the entire year 2006.

5.4.2.2.2 Simulation of the secondary reserve market

The simulation of the secondary reserve market is similar to the simulation of the primary reserve market. Once per year the secondary reserve market is executed for the entire year. The grid operator places a price independent ask for 3.3 GW of positive reserve capacity. Since negative reserve capacity is not lost on other markets, it is not modelled in the simulation model. Again the supply side is modelled by a reserve market trader for every player. The calculation of the bid price for capacity is based on the algorithm described for the primary reserve in Formula 5-10. Again nuclear plants and lignite plants with an installed capacity above 30 MW bid 5 % of their net capacity into the market. In addition hard coal power plants with an installed capacity above 30 MW bid 10 % of their net capacity into the market. Pump storage plants bid their full capacity into the market. Every plant bids its variable cost into the market. But as the actual utilization of reserve capacity in terms of reserve energy is not analysed in this thesis, the utilization according to the work price is not simulated.

5.4.2.3 Minute reserve (tertiary reserve)

5.4.2.3.1 Description

The minute reserve or tertiary reserve is utilized in order to free the secondary reserve. It has to be available within 15 minutes. The activation of the minute reserve is carried out manually. The normal activation time of minute reserve is up to on hour. In case of serious imbalances of the grid the activation can be extended to several hours. The minute reserve is purchased by the transmission grid operators in a day-ahead tender. Due to the lower technical requirements participation in this market is higher. As an example 11 players took part in the minute reserve market of the Eon zone in 2006 (Türkucar, 2006). After a period of differing time schedules and procedures for the purchase of minute reserve by the four German grid operators the German regulator determined common rules for this market in 2006 (Bundesnetzagentur, 2006). For the bidding procedure the day is divided into periods of four hours. The market is cleared separately for every period. Similar to the secondary reserve the minute reserve is compensated by a capacity price and a work price in case of execution. The tendering procedure for minute reserve is executed before the closure of the German spot market. Market results of the minute reserve are available at 11:00 while the spot market auction closes at 12:00. The amount of minute reserve capacity purchased varies slightly on daily level. In general ca. 3 GW of positive reserve capacity and ca. 2 GW of negative reserve are purchased. Due to the high volatility of the prices an estimation of the market volume is more difficult than for the other reserve markets. But published prices (Theobald et al., 2003, p.44 ff.) indicate that the cost for capacity for one year is within the range of several hundred million Euros per year.

5.4.2.3.2 Simulation of the minute reserve market

A recent study shows that the actual utilization of minute reserve is rather low (Theobald et al., 2003, p.92 ff.). Although the minute reserve market is executed before the spot market, it is not likely that it has a major impact on the spot market results. As long as there is enough capacity in the electricity markets it is expected that capacities are bid into the minute reserve market which have variable cost above the expected spot market prices for the given period. Therefore the minute reserve market in PowerACE is executed after the spot market. The main goal of the integration of the minute reserve market into the simulation is to ensure that the capacity demand of the real world electricity market is met. The market results themselves are not analysed. It is difficult to determine an adequate bidding strategy for the minute reserve market. Since the minute reserve market is not within the centre of the analysis, a simple bidding strategy is integrated to ensure market operation. In the current implementation of the market supply bidders bid their entire capacity which is not sold in the other markets on the minute reserve market. The work price is based on variable cost and the capacity price is calculated by multiplying the work price with the length of the time period.

5.5 Simulation of pump storage plants

Pump Storage plants can be used to balance the electricity system. In times of low electricity prices electricity is used to pump water to a storage on higher ground. In cases of peak prices the water is used to generate electricity. Currently pump storage plants represent the most important way to store electricity in an indirect way. In order to integrate pump storage plants into the simulation of electricity markets two procedures have been developed. The first procedure relies on a static profile, the second procedure simulates pump storage plants in a dynamic way.

5.5.1 Static simulation

In the static simulation the utilization of pump storage power plants is integrated as an exogenous load curve which is based on the available information. An overview of the pump storage profile applied for every simulation day is given in Figure 5-15. In order to force the pump storage profile into the market, a price independent bid is placed on the spot market. If this setting is applied, pump storage plants cannot bid into the reserve markets. The advantage of this solution is that in this setting pump storage plants do not interact with other effects in the market. This can be useful for the analysis of single effects. Another aspect is that it helps to save computational resources.

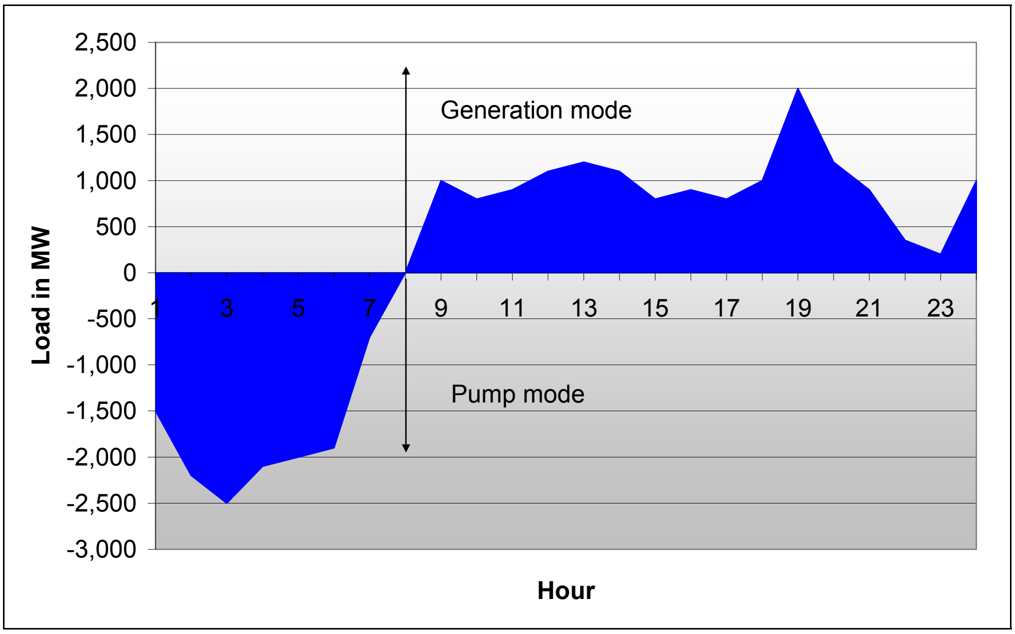

Figure 5-15: Pump storage load profile
Source: Verband der Elektrizitätswirtschaft [VDEW], 2000

5.5.2 Dynamic simulation

The dynamic simulation of pump storage power plants is a complex issue since pump storage can bid on several markets. Another important issue is the fact that technical restrictions such as the storage volume have to be taken into account. The basic input for the dynamic simulation is a database on the German pump storage plants. It is given in the Appendix. The core of the simulation of pump storage plants is to determine an optimal utilization of the plants based on given technical restrictions. The first step is creating a price prognosis for a given period. The price prognosis is created according to the algorithm described in 5.3.6. In order to determine the maximum income and the corresponding utilization of a given plant an algorithm is developed which optimizes the utilization of each pump storage plant. The mathematical formulation of the algorithm is given in Formula 5-11. If the trading on the minute reserve market for pump storage plants needs to be integrated into the simulation, the algorithm can be extended according to the next formula.

Formula 5-11: Algorithm for the utilization of pump storage power plants

$$\varepsilon_e = Max\sum_1^{\beta}\begin{cases}\varpi \cdot \eta \cdot \varphi_h & if \quad \varpi \le 0 \\ \dfrac{\varpi}{\eta} \cdot \varphi_h & if \quad \varpi > 0\end{cases}$$

Conditions:

1. Capacity restriction: $0 \le |\varpi_h| \le g, \forall\, h \le \beta$
2. No storage underflow: $s_0 + \sum_1^h \varpi_h > 0, \forall\, h \le \beta$
3. No storage overflow: $s_0 + \sum_1^h \varpi_h < \theta, \forall\, h \le \beta$
4. Initial storage status equals end status $s_0 = s*$

Legend:

Variables			Unit	Indices
g	=	Generation capacity	[MW]	h = Hour
s*	=	Final storage status	[MWh]	e = Spot market
s_0	=	Initial Storage status	[MWh]	
β	=	Last hour of planning period	[None]	
ε	=	Profit	[Euro]	
η	=	Efficiency	[%]	
θ	=	Volume of the storage	[MWh]	
φ	=	Predicted price of spot market	[Euro/MWh]	
ω	=	Planned operation	[MW]	

Formula 5-12: Optimization of pump storage plants on spot market and reserve market

$$\varepsilon = Max\begin{cases}\varepsilon_e \\ \varepsilon_r\end{cases}$$

Legend:

Variables			Unit	Indices
ε	=	Profit	[Euro]	r = Reserve market
				e = Spot market

The actual calculation within the simulation platform is carried out by sorting the price forecast in ascending and descending order. In the next step the algorithm cycles through both price lists and matches price pairs of both lists as long the operation of generation in hour x and pumping in hour y creates a positive income with the given efficiency of the plant. After matching a pair of prices, the maximum capacity for operation in both hours is determined by checking the storage status and the capacity of the plant for the entire period. Another condition for the algorithm is that the initial storage status is equal to the storage status at the end of the planning period. For the analysis carried out in this thesis it is assumed that the initial storage status is 50 % of the total storage volume. Based on this algorithm the optimal utilization of each pump storage plant can be calculated for any period.

Another problem which has to be taken into account is that the operation of a pump storage plant with a capacity of several hundred MW can have an impact on the prices itself. Therefore the algorithm can also be used with an option which creates a new price forecast for every plant by considering the planned operation for the previous plant.

After the development of an algorithm for the optimal utilization of every pump storage plant the next issue is to determine the bidding behaviour on the electricity markets. Since primary reserve is activated automatically within running generation units it is assumed that pump storage plants do not bid into the primary reserve market due to technical restrictions. The secondary reserve market is an interesting market for pump storage plants as they can meet the technical requirements. In addition capacity payments in this market are relatively high. The next market is the minute reserve market. Since the actual utilization of the minute reserve is rather low, the balancing capabilities of pump storage plants are wasted in the market. Therefore it is assumed in the case studies of this thesis that pump storage plants to do not bid into the minute reserve market, which also helps to simplify the problem. The remaining spot market is a very attractive market for pump storage plants since they can create profits on volatile market prices. As consequence of the discussion above pump storage plants can bid into the secondary reserve market and the spot market for the simulations within this thesis.

As described in 5.4.2.2, the secondary reserve market is executed once per year within the model. In order to determine the capacity price for the bid into the secondary reserve market the possible profits of the alternative operations on the spot market for the analysed period have to be calculated. Although the algorithm is capable to do that, the calculation time of the algorithm for the optimization of 32 plants for a time horizon of 8760 hours is unbearable for a simulation model as the time needed for the calculation grows in a non-linear way. The time horizon for the calculation of the potential average daily income for pump storage plants on the spot market can be varied. In order to determine the impact of the time horizon on the calculation time, the time horizon is varied and the required time for one simulation run of one year is determined. The results of this procedure are presented in Figure 5-16. The experiment is carried out on a fast desktop PC[7]. The results show that the influence of the pump storage algorithm on calculation times is neglectable for a time horizon of a few days. However, for longer time horizons the calculation time grows heavily. Starting with a calculation time of ca. 30 seconds for a time horizon of 7 days, the calculation time grows to more than 20 hours for a time horizon of 364 days. Having in mind that the case studies carried out in this thesis require a few thousand simulation runs the calculation time of 20 hours for one run is not acceptable. Therefore the capacity price of every pump storage plant is analysed for different time horizons and compared to the capacity price for a time horizon of 7 days. The analysis shows that the influence of the time horizon on the capacity heavily depends on the ratio of

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storage volume and installed capacity. Plants with a higher storage capacity ratio tend to create higher incomes with longer time horizons. Plants with a smaller ratio show an opposite effect which is caused by lower incomes in the summer period. In order to reduce the calculation time of the model, the income ratio of the calculated capacity price for a time horizon of 364 days and a time horizon of 7 days is calculated.

Formula 5-13 Calculation of the income ratio

$$r_i^* = \frac{\left(\frac{p_{364}}{g_i * 364}\right)}{\left(\frac{p_7}{g_i * 7}\right)}$$

Legend:

Variables			**Unit**	**Indices**		
r*	=	Income ratio of pump storage plant p	[None]	i	=	Index of plant
p^*_{364}	=	Simulated capacity price for 364 days	[Euro]			
p^*_7	=	Simulated capacity price for 7 days	[Euro]			
g	=	Generation capacity	[MW]			

The standard time horizon for the calculation of the capacity price on the secondary reserve market is set to 7 days. In order to reduce the error caused by this assumption, the calculated capacity price of every plant is multiplied with the income ratio determined according to Formula 5-13: The income ratio for every plant is given in the Appendix.

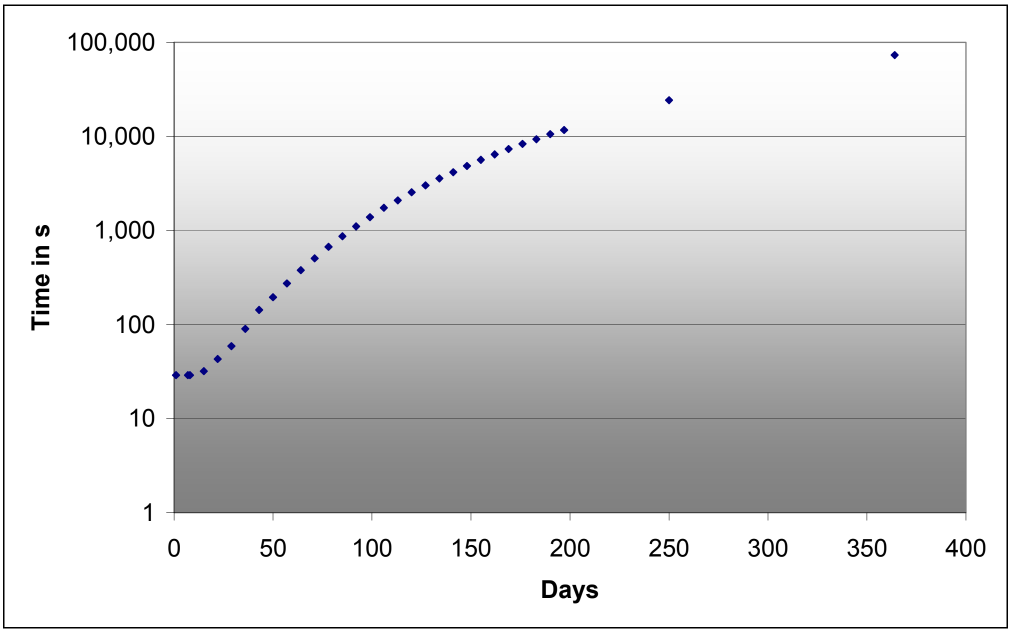

Figure 5-16: Impact of the time horizon for pump storage optimization on calculation time
Source: own illustration

After the closure of the secondary reserve market the remaining capacity of pump storage plants is bid into the spot market on day-ahead basis. In order to determine the load profile for the bid, the developed algorithm is utilized based on a day-ahead 24 h price prognosis. The resulting load profile is bid into the market by a price independent bid.

5.6 Model management with the PowerACE Cluster System

The simulation of electricity prices for an entire year or several years on hourly level leads to an enormous amount of data that needs to be checked and analysed. If it is taken into account that a normal scenario consists of 50 simulation runs in order to level out the impact of the random generator, things become even more complex. The data produced for a scenario consisting of 50 simulation runs amounts to 470 Megabyte [MB] in the minimum case. This figure shows that the amount of data generated by the simulation platform cannot be handled without the support of additional tools. Therefore additional tools for the analysis and aggregation of the models results have to be developed.

Another important issue is the required computing power and the resulting calculation time. The examples of the pump storage optimization given in Chapter 5.5.2 show that calculation times can easily explode. Even with the described measures to speed up the simulation a simulation run for one year requires a minimum of 30-40 seconds on a modern high speed desktop PC[8]. As a single scenario with a single model setup requires 50 simulation runs, the calculation time reaches a minimum of 30-40 min. This does not sound much, but it has to be taken into account that the calibration procedures or case studies with parameter variations require several thousand simulation runs which can easily reach calculation times of several days on a single computer. The amount of data produced in these cases reaches more than 20 Gigabyte [GB]. These examples underline the necessity of developing solutions to utilize more computing power in order to speed up the analysis.

The last crucial problem dealing with the management of the developed model is the management of model settings. Most settings of the developed model are stored in XML [Extensible Markup Language] files. All in all the XML statements for the simulation settings reach more than 550 lines. Especially in cases where a huge number of scenarios with varying parameters (e. g. variation of CO_2 prices or fuel prices) have to be calculated the management of model settings becomes a problem.

In order to deal with these issues and keep the developed model manageable, the PowerACE Cluster System has been developed. The PowerACE Cluster System consists of several modules developed to deal with the issues described above. The PowerACE Analyzer is developed for the automated analysis of PowerACE results. The PowerACE Cluster Management helps to utilize several PCs or processor cores of multi-core computers in parallel in order provide more computing power. The developed Scenario Creator provides a graphical user interface for the automated generation of scenario files. These main parts of the PowerACE Cluster system are described in this section.

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5.6.1 Analysis Tools

The first step for the automated analysis of simulation results is the standardized output of the data produced in the simulation. Therefore all data logged in the simulation is created by the developed "UniversalDataLogger" providing a standardized format for the output of data on different time scales. The data is logged in ".csv" files. The UniversalDataLogger also provides an adequate folder structure in order to facilitate further analysis. The next step is the development of an adequate tool for the automated analysis. Therefore the first task is the aggregation of the data produced by all simulation runs within one scenario. The developed PowerACE Analyzer cycles through all the result files and copies all the data of a given category into one Excel-file and calculates the average of the entire data set. An example for a possible result is the average spot market price in a given hour. In order to provide additional information the minimum, maximum and average values and the standard deviation of the entire time series for one year are calculated. In cases of simulations for several years these indicators are stored in an additional sheet and figures of the annual development of every indicator are created in order to speed up the analysis. Since the analysis of spot market prices plays an important role in this thesis, additional features have been implemented in order to speed up the calibration of the model. The EEX prices of the years 2001 to 2006 are stored within in the developed tool. If the tool is run for one of these years, it automatically creates a comparison of the simulated time series and actual price development. In order to exclude extreme price events the time series can be filtered. The filtered and ordered time series of hourly prices are automatically displayed in a graph. In addition a graph comparing the daily average prices is created. For more detailed information a summary sheet is created which sums up important indicators for the comparison of both time series. An overview of the output of the developed analysis tool is given in Table 5-8 and Table 5-9.

Table 5-8: Model output available for automated analysis

Indicator available for the analysis					
1	Total load	8	Installed generation capacity	15	CO_2 price
2	Renewable load	9	Available generation capacity	16	Capacity price (Primary reserve)
3	Remaining system load	10	Installed generation capacity per fuel	17	Capacity price (Secondary reserve)
4	Relation of load and avaiable capacity	11	Average efficiency of plants per fuel	18	Cost of the primary reserve
5	Market volume	12	Utlization of plants	19	Cost of the secondary reserve
6	Renewable market volume	13	Utilization of plants per fuel	20	
7	Profit	14	CO_2 emissions	21	

Due to the number of indicators and the disk space required for the analysis a graphical user interface is developed where the user can select the variables to be analysed by the analysis tool. The parameters selected by the user are stored in an XML file which is read by the

PowerACE Analyzer. An example of the Evaluation Selector is given in the Appendix (Figure A-1).

Formula 5-14: Definition of Profit

$$\varepsilon_h = \sum_i \begin{cases} m_h - c_{i,h} & if \quad m_h > c_{i,h} \\ 0 & otherwise \end{cases}$$

Legend:

Variables			Unit	Indices		
c	=	Variable cost	[Euro/MWh]	i	=	Plant
ε	=	Profit	[Euro]	h	=	Hour
m	=	Spot market price for electricity	[Euro/MWh]			

Table 5-9: Indicators and figures created by the PowerACE Analyzer

Analysis of all hourly indicators		
Indicators (simulation run)	**Indicators (scenario)**	**Figures (scenario)**
Sum (annual) Minimum (annual) Maximum (annual) Standard deviation (annual) Average (annual)	Sum (annual) Minimum (annual) Maximum (annual) Standard deviation (annual) Average (annual)	Sum (annual) Minimum (annual) Maximum (annual) Standard deviation (annual) Average (annual)
Additional analysis for spot market prices		
Benchmark	**Benchmark figures**	
Ø price (€/MWh) Minimum price (€/MWh) Maximum price (€/MWh) Standard deviation Correlation	Filtered and sorted prices Average daily prices	

In order to help to enable the user to distinguish different scenarios and their corresponding model version, the PowerACE Analyzer copies the entire PowerACE model with the setting files, the databases and the result files to a folder on the network. In a last step the user is notified per email about the finished analysis and the network position of the copied data. An overview of the structure of the PowerACE Analyzer is given in Figure 5-17.

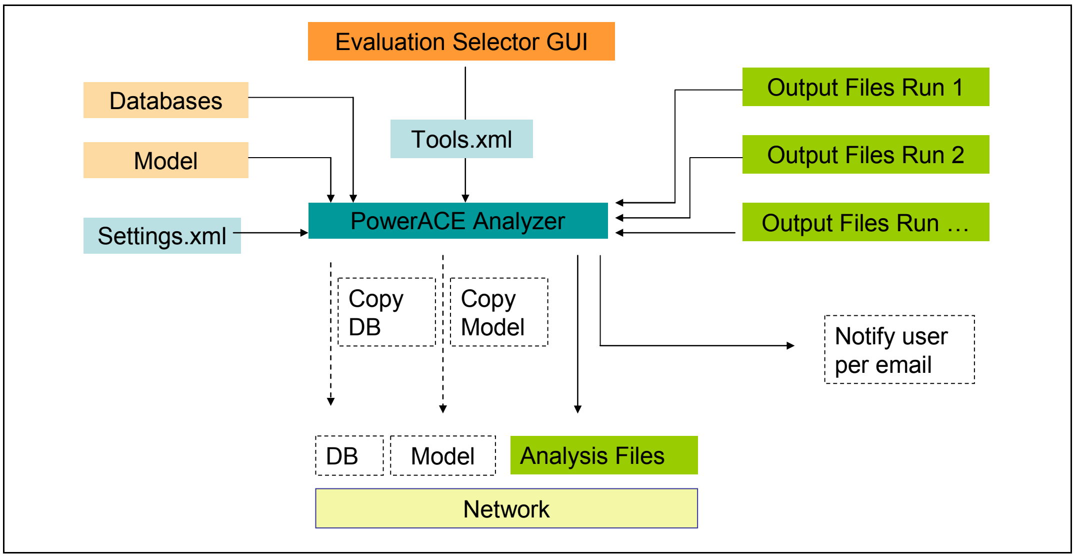


Figure 5-17: Structure of the PowerACE Analyzer
Source: own illustration

In addition to the PowerACE Analyzer implemented in Java a number of additional Tools based on MS Excel are developed which apply Visual Basic methods in order to carry out further analysis for the case studies presented in the next chapter.

5.6.2 Scenario Creator

Another important part of the PowerACE Cluster System is the Scenario Creator. The Scenario Creator is a graphical user interface which helps to generate the xml-based parameter files required for a PowerACE Simulation. The Scenario Creator can be run in different modes. The first mode helps to create a number of single scenarios by varying single parameters manually. In order to get scenario specific analysis with the PowerACE Analyzer, the Scenario Creator is also linked with the Evaluation Selector GUI. The second mode of the Scenario Creator is far more complex since it allows for the creation of parameter sweeps. The user can select single parameters and specify the start value, the end value and the step size between these values, and the Scenario Creator creates all scenario files necessary for the number of scenarios to be created. A further extension of the Scenario Creator is the possibility to create nested parameter sweeps. Nested parameter sweeps can for example be used to search the optimal setting in a parameter space of several parameters. The user can select several parameters and a start value, an end value and the step size for each parameter. If a nested parameter sweep is created the Scenario Creator determines all possible combinations of the selected parameter space and creates the corresponding scenario files for each combination. Depending on the number of variables and the number of steps for each variable, the number of created scenarios can be huge. The creation of nested parameter sweeps requires a complex algorithm which is capable to deal with parameters of different types (Objects, Integers, Floats…). The developed algorithm utilizes Hash Maps in order to manage the different types of parameters. An example of the graphical user interface of the Scenario Creator is given in Figure A-2. After the creation of the parameter files required for the PowerACE simulation run an additional xml-file is created which contains the most important information of the created scenarios such as an estimation of the required disk space or the number of the scenarios. This xml-file can be used for the automated management of the created scenarios in the cluster management system. An overview of the structure of the developed Scenario Creator is given in Figure 5-18.

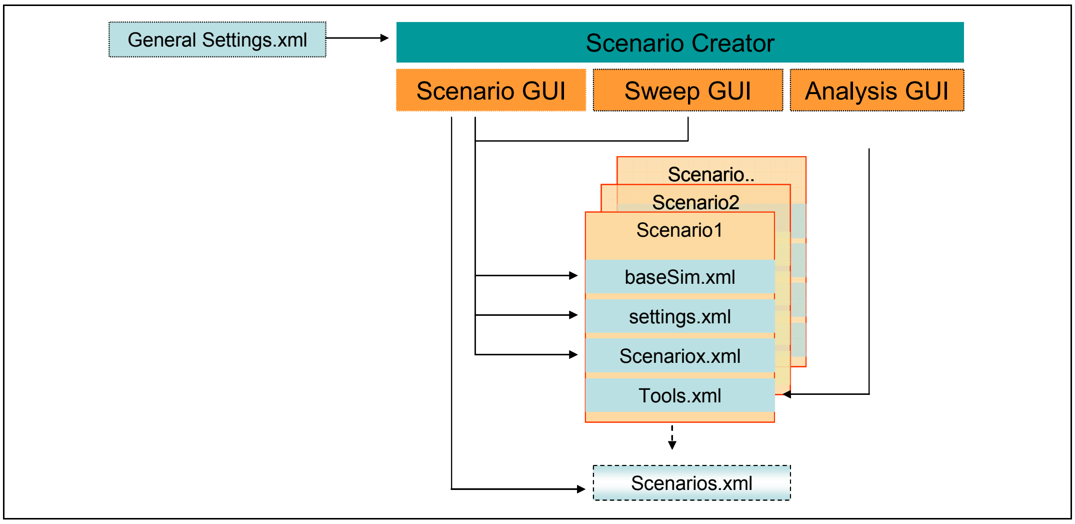


Figure 5-18: Structure of the developed Scenario Creator

Source: own illustration

5.6.3 Cluster Management

The centre of the PowerACE Cluster System is the PowerACE Cluster Management. The PowerACE Cluster Management fulfils two major tasks: 1. The utilization of several computers or processor cores in order to speed up PowerACE simulation runs, 2. The management of different scenarios by sequential or parallel calculation. The PowerACE Cluster Management is made up of three modules in order to fulfil this task. This first module is the Core Manager. The Core Manager reads a database where all the necessary data on the available computers are stored. This data consists of PC-name, processor, computing power, memory, number of cores and the operation system. The available information on the computers is displayed in a graphical user interface. Based on the displayed information, the user can select the computers to be involved in the simulation (see Figure A-3 for a picture of the interface). The Core Manager passes the information of the available computing units to the Software Distributor and starts the Cluster Watch which checks the physical availability of the selected computing units in predefined time steps. If one of the selected computing units fails to reply, e. g. because of technical problems (e. g. loss of network connection or power connection), it is deleted from the list of available computing units within the cluster and the status of the task assigned to the given computer is set to its initial status. A crucial issue for the calculation and analysis of several scenarios is to ensure that the same versions of PowerACE, the necessary databases and the Analyzer are applied for the simulation. This task is carried out by the Software Distributor. The Software Distributor connects the selected computing units and copies the predefined software to the target computer. In order to increase the safety of this process the existing versions of the software are deleted on the target computer. All communication between the computers involved in the cluster takes place via SSH connection (Secure Shell). In case of the Software Distributor the Software Distributor creates two batch files. The first batch opens the SSH-connection, copies the second file to the target computer and executes it. The second batch file contains the necessary commands, e. g. for the copy process of the PowerACE model. Once the software distribution is finished the target computer creates a predefined folder on the network. The Core Manager checks for the availability of this folder in defined time steps. If the folder is detected, the Core Manager passes the information of a free computing unit to the Scenario Manager. The Scenario Manager reads the Scenarios.xml file with the information on the scenarios to be calculated in the simulation. Based on the given information on the available computing units (processor cores), the Scenario Manager assigns a scenario for each available computing unit and creates the necessary batch files in order to copy the necessary parameter files to the target computer and starts the simulation on the target computer. The status of the computing unit is set to "working". If one of the involved computing units has finished the calculation of its assigned scenario, two additional predefined folders are created. The first folder contains the number of the scenario and determines which scenario has been finished. This folder is detected by the Scenario Manager and the given scenario is deleted from the list of remaining scenarios. The second folder created by the computing unit contains its name. This folder is detected by the Core Manager and the computing is registered as a free unit. As long as not all scenarios are finished, the free core is again passed to the Scenario Manager which assigns another scenario to the computing unit. The described cycle between the programmes and computing units continues until all scenarios are calculated. The described Cluster Management can also be used on a single computer for the sequential calculation of several scenarios e. g. over night.

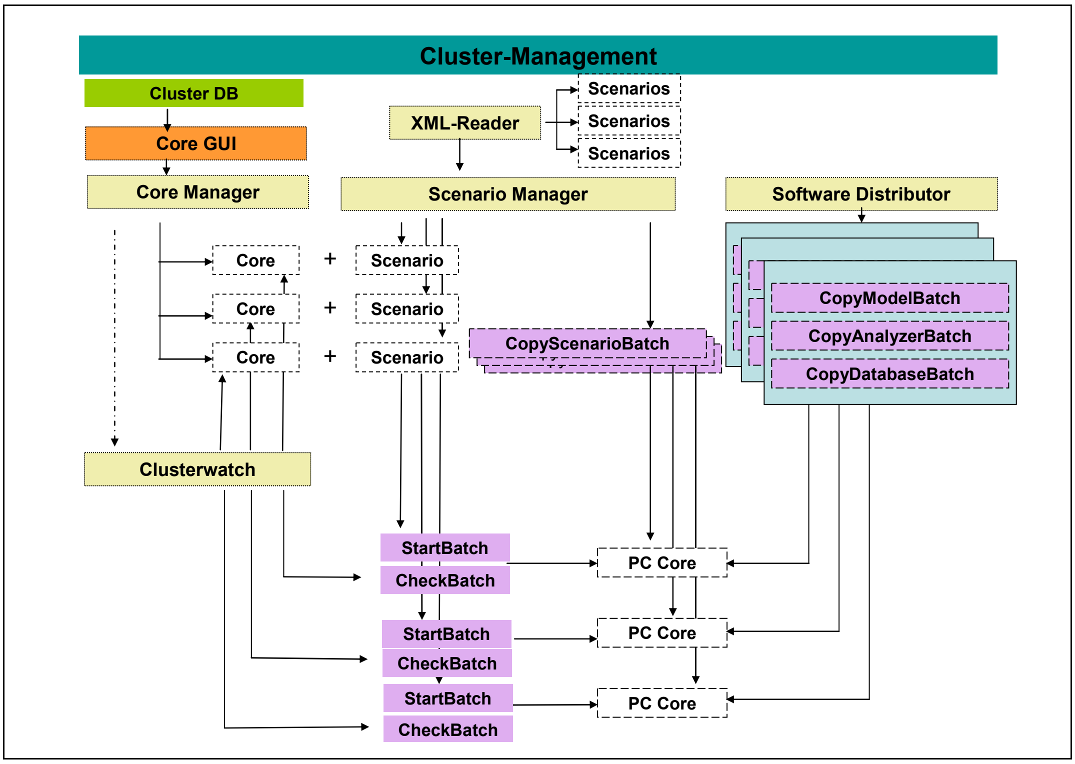


Figure 5-19: Structure of the developed Cluster Management

Source: own illustration

5.6.4 Interaction of the developed modules

The developed PowerACE Cluster system is characterized by a complex interaction of the developed modules PowerACE, PowerACE Analyzer, Cluster Management and Scenario Creator. In order to enable a stepwise improvement of the single modules, the modules have to fulfil the following criteria: The developed modules have to be capable of running as a single stand alone application and as an integrated part of the PowerACE Cluster System. The requirement of a stand alone application is also helpful if a single application within the Cluster System crashes and the developed system can be restarted with the remaining tasks. However, in most cases the developed modules run within the PowerACE Cluster System. The typical interaction of the PowerACE Cluster System is presented in Figure 5-20.

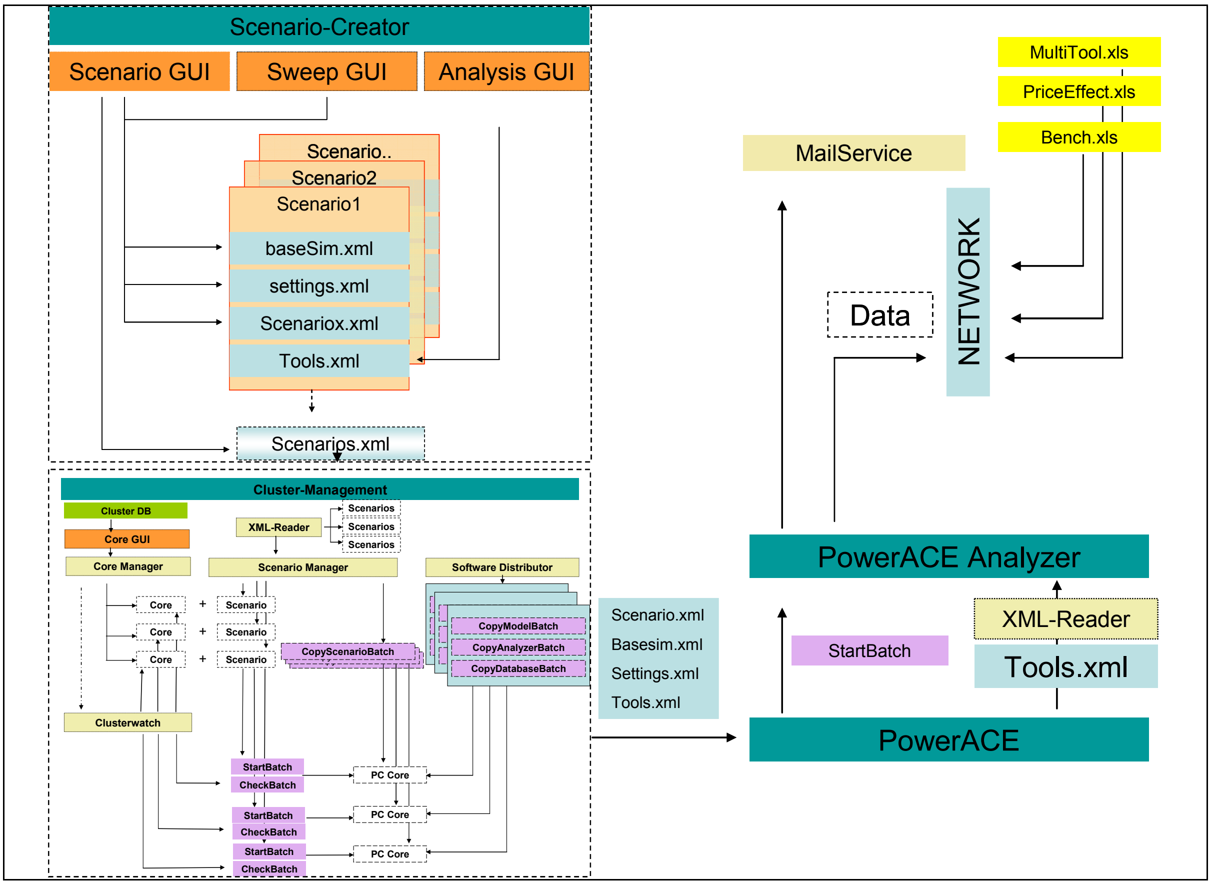


Figure 5-20: Structure of the PowerACE Cluster System
Source: own illustration

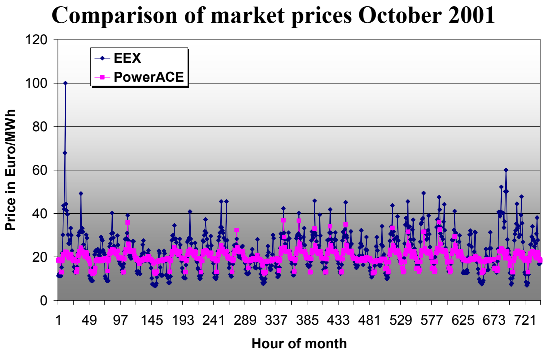
The first step is to create the scenarios to be calculated with the Scenario Creator. The Scenario Creator creates the required xml-files for the simulation and the PowerACE Analyzer. The aggregate information on the created scenarios is stored in the file "Scenario.xml". Thereafter the Cluster Management is started. The Cluster Management reads the "Scenarios.xml" in order to get the information on the scenarios to be calculated. The user can select the computer to be involved in the cluster. Based on the given information the Cluster Management copies the software and the created parameter files to the target computer and starts the simulation on the target computer. The target computer carries out the simulation. If the simulation on the target computer reaches the required number of runs, the PowerACE model starts the PowerACE Analyzer. The PowerACE Analyzer carries out the required analysis and copies the software and the result files to the network and notifies the user per email. Once the computer has finished his tasks the Cluster Management assigns a new task to the computer. If all scenarios are finished, the user can manually start the developed Visual Basic Tools in order to carry out a specific analysis with the generated data set.

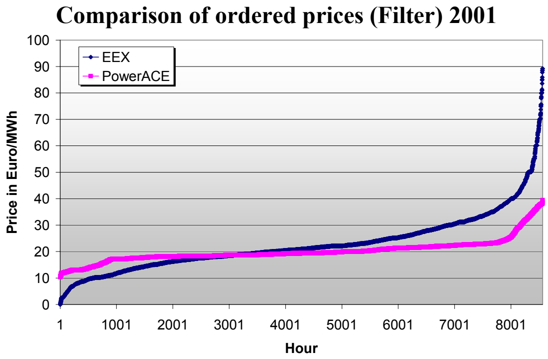
5.7 Calibration and evaluation of the developed model

The central task of the developed simulation platform is the simulation of spot market prices in Germany. Therefore it seems to be important to compare the results of the developed model to market prices on the German spot market EEX. This seems to be even more important if the enormous number of input data is taken into account which needs to be validated. Due to the availability of detailed data on renewable energy the years 2001, 2004, 2005 and 2006 have been selected for a detailed comparison of the market results. In 2005 and 2006 the complexity increases due to the beginning of the European Emission Trading System.

5.7.1 Calibration for the years 2001 and 2004

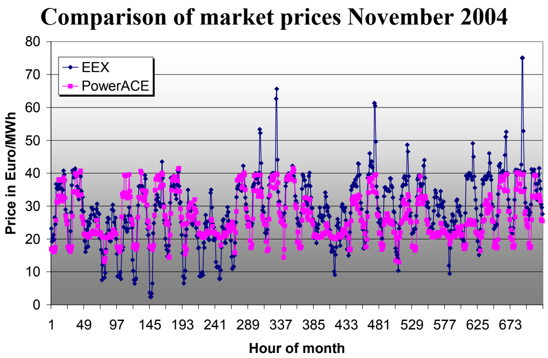
A first comparison between the time series of hourly prices of the German spot market in 2001 and the average simulated prices of 50 simulation runs with the PowerACE model shows a low correlation and a considerable underestimation of the annual average price. However, a closer look at the actual spot market prices in 2001 shows that market prices of up to 998 Euro/MWh are reached, which indicates gaming on the market during few hours throughout the year since these are price cannot be justified by generation cost. In order to reduce these effects, 54 hours with market prices above 90 Euro/MWh are filtered from the time series. After the filtering procedure the Pearson's correlation coefficient between both time-series rises to 0.66 and the difference of the average market prices reaches 2.65 Euro/MWh. A comparison of both time series for October is given in Figure 5-21. The correlation shows that the underlying data sets concerning electricity demand, renewable electricity generation and power plant portfolio are adequate to provide a basis for the analysis of market developments. Besides the underestimation of peak market prices two other phenomena can be discovered. In times of low demand actual market prices can fall below the simulated generation cost expected by the PowerACE model. A possible explanation of this effect can be that market participants misjudged market developments in their bidding strategy. Another reason could be that generation companies want to keep their plant online due to technical restrictions, e. g. in order to avoid a shut down of a plant. The second phenomenon is the fact that the model results underestimate the volatility of market prices at the weekend. This aspect could be an interesting issue for further investigation in the future. Possible explanations could be low liquidity on the market or the preferred scheduling of plant maintenance at the weekend leading to a considerable reduction in the available capacity.

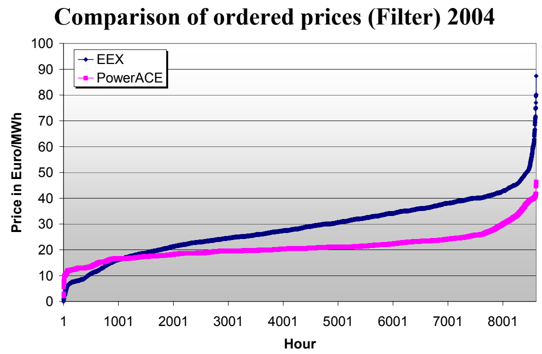




Important indicators for the year 2001

2001	EEX (Filter 90)	PowerACE (Filter 90)
Ø price (€/MWh)	22.76	20.11
Min. price (€/MWh)	0.00	10.37
Max. price (€/MWh)	89.19	39.42
Standard deviation	10.83	4.24
Net production (TWh)	533.09	526.41
Pearson Correlation	0.66	





Important indicators for the year 2004

2004	EEX (Filter 90)	PowerACE (Filter 90)
Ø price (€/MWh)	28.50	21.25
Min. price (€/MWh)	0.00	2.06
Max. price (€/MWh)	87.41	46.32
Standard deviation	10.60	5.22
Net production (TWh)	554.01	549.75
Pearson Correlation	0.61	

Figure 5-21: Comparison of market prices and model results for the years 2001 and 2004

Source: own illustration, market prices: European Energy Exchange [EEX] (2006b); European Energy Exchange [EEX] (2006c)

Probable reasons for the remaining differences may be lower generation costs or aspects related to forecasting or trading errors. The interpolation algorithm applied in the EEX closed auction for single hours can lead to prices below the cost of the marginal generation unit if some units such as nuclear plants bid at zero cost to avoid a shut-down. Another aspect which has to be taken into account is that the entire electricity demand is not traded on the real world spot market. Other markets like the OTC/Future market might have an additional impact on the spot market. The results of the comparison for the year 2004 are similar. The EEX prices generally tend to be higher than the PowerACE prices in the peak load. If a filter of 90

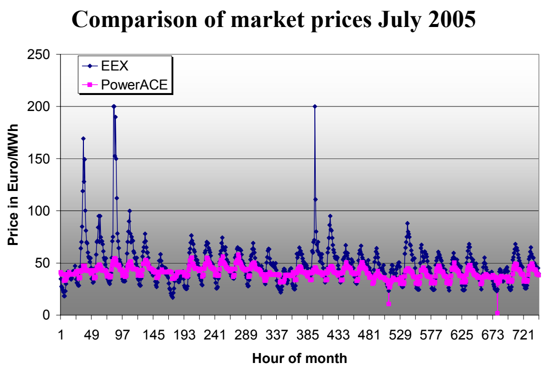
Euro/MWh is applied, the correlation reaches 0.61. The underestimation of the market price is slightly higher. But the difference in the volatility of the market is lower and reaches 5.38 Euro/MWh. An overview of the main indicators of the calibration of the years 2001 and 2004 is given in Figure 5-21.

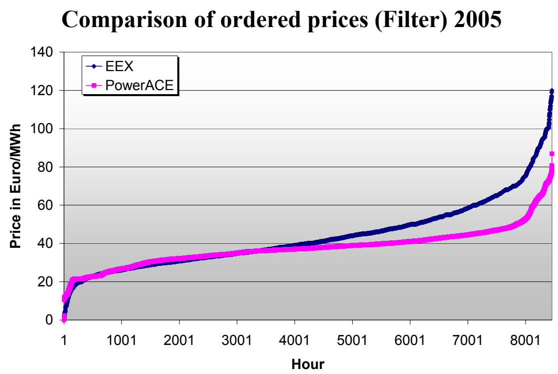
5.7.2 Calibration for the years 2005 and 2006

In 2005 the situation is more complex. The introduction of the European emission trading system creates the CO_2 prices as a new input factor for the calculation of electricity prices. Since the emission permits have been allocated for free by the national allocation plan in Germany, an important question is how much of the CO_2 price is integrated into the calculation of the bid price. In order to determine the likely CO_2 price factors for the different power plants a case study has been carried out in cooperation with the University Karlsruhe. A detailed description can be found in Genoese et al. (Genoese et al., 2006). In the case study the CO_2 price factors are varied for each fuel until the ordered market curve and the correlation shows the best fit to the real market prices on the German spot market. The result is that it is assumed that the CO_2 price is integrated to 100 % into the calculation of the bid price of gas fired plants. In case of hard coal and lignite fired plants the factor reaches only 85 % and 70 %. This result is somewhat surprising since economic theory would expect that the price of every production factor is integrated to 100 % into the calculation of the bid price. A possible explanation for the lower price factors could be the allocation rule of grandfathering with ex post judgement where certificates which have not been used by a plant have to be given back at the end of the trading period. Ca. 15 % of the allocated emissions are subject to this rule (Genoese et al., 2006, p.21). Another reason could be long-term take or pay contracts for fuels which could prevent a lower utilization of existing plants. The results of the comparison for the year 2005 are similar to those of the years presented above. Due to the higher price level the filter is set to 120 Euro/MWh. As a consequence of the increasing number of hours with very high prices this filter excludes 159 hours from the analysis. The correlation of the filtered time series reaches 0.64. Again peak prices are generally higher in the real world market.

A similar calibration procedure is carried out for the year 2006. The resulting CO_2 price factors for gas and hard coal reach 100 % for the year 2005. Exceptions are lignite fired plants. The best results can be reached for a CO_2 pricing factor of 20 %. This result cannot be explained easily. One possibility could be that companies want to keep the utilization of lignite plants on a high level for strategic reasons. Another reason could be caused by the fact that companies owning lignite power plants also own the related mines. Since lignite can hardly be transported for long distances due to its low energy content, lignite power plants and lignite mines are perhaps considered as one planning unit. In this case the total fuel cost of lignite power plants are no longer considered as variable cost, but as fixed cost since the mines are designed for a given output level. In a recent study it is stated that only ca 30 % of the fuel cost for lignite are variable mining costs (Energiewirtschaftliches Institut an der Universität zu Köln (EWI) and Energy Environment Forecast Analysis (EEFA) GmbH, 2007, p. 9). As a consequence the utilization of lignite power plants is likely to react only to a very limited extent to moderate CO_2 emission prices. This is an aspect which could heavily affect possible emission reduction strategies in Germany since lignite fired plants are characterized by the highest CO_2 emissions.

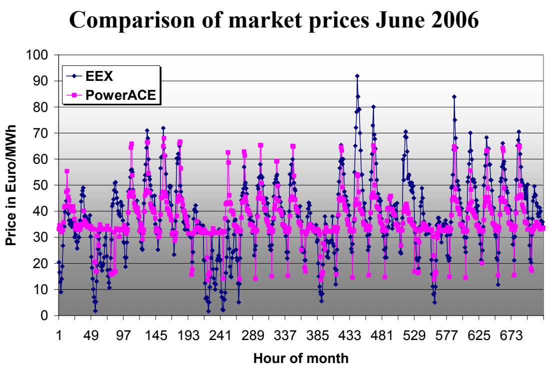
Furthermore electricity imports based on foreign nuclear or hydro plants could have some influence on the prices in times of low electricity demand which could have an impact on the calibration of the model. A closer analysis of this issue would require a European simulation model. The comparison of the key indicators shows a correlation of 0.64 for the year 2006 if a filter of prices above 125 Euro/MWh is applied, which excludes 147 hours with very high prices from the further analysis. Volatility and market prices have increased again beyond a level that can be explained by the model. An overview of the key indicators is given in Figure 5-22.

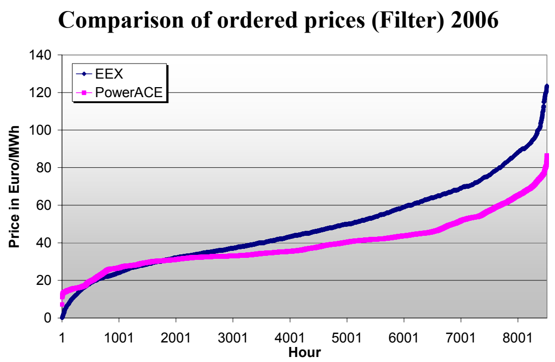




Important indicators for the year 2005

2005	EEX (Filter 120)	PowerACE (Filter 120)
Ø price (€/MWh)	43.52	37.73
Min. price (€/MWh)	0.00	0.00
Max. price(€/MWh)	119.98	86.90
Standard deviation	17.61	9.76
Net production (TWh)	557.88	555.49
Pearson Correlation	0.64	





Important indicators for the year 2006

2006	EEX (Filter 125)	PowerACE (Filter 125)
Ø price (€/MWh)	48.31	39.46
Min. price (€/MWh)	0.00	7.17
Max. price (€/MWh)	123.60	86.41
Standard deviation	22.04	13.33
Net production (TWh)	559.08	556.76
Pearson Correlation	0.64	

Figure 5-22: Comparison of market prices and model results for the years 2005 and 2006

Source: own illustration, market prices: European Energy Exchange [EEX] (2006a); European Energy Exchange [EEX] (2007e)

5.7.3 Evaluation of the calibration

The high correlation for all analysed years shows that the underlying data sets concerning electricity demand, renewable electricity generation and power plant portfolio are sufficient as a basis for the analysis of market developments. Since the model assumes that the entire electricity required is traded at spot market prices, it makes sense that it does not mirror the extreme price events of the real spot market. Additional bidding strategies and learning algorithms for the agents are therefore not applied to avoid creating extreme price events. Besides the underestimation of peak market prices three phenomena can be observed which could be subject to further research: 1. The volatility of the weekend tends to be higher than expected by the model. 2. There are some hours where the real spot market shows prices which are below the expected generation cost. 3. The price factors for the integration of the CO_2 prices determined in a calibration procedure are below the values that can be expected by economic theory, especially in case of lignite power plants.

Besides these issues the central question for this thesis is how the quality of the model results can be assessed. To the knowledge of the author there is no model publicly available which produces results on a similar level of detail. The only time series that contains market prices on the same level of detail are the market prices of the EEX. Although the pure time series of the EEX does not allow explaining the underlying reasons for price development in the same way as a model, the comparison of the EEX time series with each other can give some insights into the quality of the time series of PowerACE. In order to compare the time series, EEX prices above 120 Euro/MWh are filtered for every year reducing the comparable time series to 8376 hours. Standard deviation and average market price are calculated for each year. In addition the correlation of each time series to the year 2005 is calculated. The comparison of the time series shows that the correlation of the PowerACE prices and the prices of the EEX in the year 2005 is considerably higher than the correlation of any other EEX time-series to the EEX prices in the year 2005. This result shows that the PowerACE simulation platform provides a better picture of the pricing tendencies on the market than the estimation of market prices of the year 2005 with the help of prices of any other year. The comparison of the average market prices shows a similar result. Again the PowerACE simulation provides the best approximation. A different result is shown by the comparison of the standard deviation. With an exception of the year 2004 the volatility of the market is higher than the results of the PowerACE model. An overview of the comparison is given in Table 5-10.

Table 5-10: Comparison of main indicators of the market prices and simulated prices for the year 2005

	2001	2002	2003	2004	2005	2006	PowerACE 2005
Pearson correlation	0.46	0.35	0.34	0.44	1	0.38	0.64
Standard deviation	11.14	11.85	13.95	10.53	17.59	21.81	9.76
Average market price	22.55	21.76	27.96	28.14	43.15	47.39	37.73

Source: market prices: European Energy Exchange [EEX] (2006a-e); European Energy Exchange [EEX] (2007e)

Despite the limitations of the model in simulating extreme market results with very low and very high prices, the significant correlation between the PowerACE results and EEX prices shows that PowerACE is a promising model for the analysis of the electricity market.

In general the comparison shows how complex it is to compare real spot market prices and a simulation. However, the results indicate that PowerACE is a reliable model for the simulation of spot market prices.

5.8 Summary and outlook

This chapter describes the developed simulation platform for the simulation of the German electricity market. Considerable effort is put in a detailed representation of the fundamental market structure and market data such as demand, renewable load and available power plants. The high level of details leads to additional requirements on the model management. Automated analysis tools are developed for the enormous amount of data produced by the model. In order to deal with the demand on computing power, a cluster management system is developed. An important aspect of the analysis carried out in this chapter is the comparison of the model results to the market prices on the German spot market. Despite all the difficulties that are connected with the simulation and comparison of spot market prices the developed simulation seems to be a good platform for the simulation of pricing tendencies on the spot market. This is underlined by the high correlation between the simulated prices and the market prices. An aspect which has to be taken into account is the fact that the simulation model is not yet able to simulate exports and imports in a dynamic way. Future work could be directed to a simulation on European level in order to get a better picture of this aspect. Other valuable extensions could be a better integration of the heat demand for a dynamic simulation of combinded heat and power plants and a dynamic simulation of plant operation in partial load mode.

6 Analysis of the impact of renewable electricity generation on the electricity sector

The analysis of the development of renewable electricity generation in Germany in Chapter 2 shows that the development of renewable electricity generation in Germany was characterized by considerable growth over the past 15 years. This development was driven by a guaranteed feed-in tariff which has been effective since 1991. The conditions of the German support scheme were revised in 1998, 2000 and 2004 (see also Laubner and Metz, 2004; Wustenhagen and Bilharz, 2006). Since 2000 the Renewable Energy Sources Act has been in place. The importance of the renewable support scheme is underlined by the past development. As a consequence of the continuous growth of supported renewable electricity generation in Germany from 18.1 TWh to ca. 52 TWh per year in the period of 2001-2006 the payments for the feed-in tariff rose according to the association of German grid operators from 1.6 billion Euro to more than 5 billion per year (Verband der Netzbetreiber [VDN], 2007d). The considerable volume of the generated electricity and the support payments leads to a number of impacts on the electricity sector.

The goal of this chapter is to analyse and quantify the most important impacts of the supported electricity generation on the German electricity sector. The developed PowerACE Cluster System is utilized in many cases in order to quantify the effects of renewable electricity generation.

In order to get a better understanding of the effects of the renewable electricity generation in Germany, it seems to be important to keep in mind how the electricity flows and how the monetary flows of the German support scheme are organized. According to the Renewable Energy Act, German grid operators have to buy electricity generated by specified renewable energy sources at a guaranteed feed-in-tariff. In a second step the electricity is then sold to the electricity suppliers according to their market-share as a month-ahead base load block. In order to deal with the fluctuating character of renewable electricity generation, the grid operators have to provide a profile service for the creation of a stable base load block. This block can be created by selling excess electricity and by buying electricity in times of lower renewable electricity generation. Additional cost of the grid operators for the integration of renewable electricity generation such as the profile service, additional reserve capacity or grid extension are integrated into the grid operation fees. These costs can be passed on to the consumers by their suppliers. Ultimately the electricity and the additional cost of the feed-in tariff have to be paid for by the consumers.

The efficiency and the cost of the renewable support scheme are the subject of a lively debate. International publications concerning the analysis of the cost and efficiency of different support schemes in Europe (Huber et al., 2004b) and the United States (Palmer and Burtraw, 2005) show that this discussion is not restricted to Germany.

A major emphasis within this analysis is given to the impact of the supported renewable electricity generation on the different markets. Important effects are the price reductions on the spot market (merit-order effect), the impact on the CO_2 market and the value of the electricity generation. In a next step the additional cost connected with the balancing and management of the system, such as necessary grid extensions, the cost of the profile service and the cost of additional reserve capacity are analysed. The third section of this chapter deals with the impact of renewable electricity generation on generation companies owning the conventional power plant portfolio. Finally the results are summarized, evaluated and followed by a discussion of the impact of the analysed effects on the different players.

6.1 Interaction of the renewable electricity generation with the electricity market and the CO_2 market

6.1.1 Value of renewable electricity generation

The first important step for the analysis of the impact of the supported renewable electricity generation is the analysis of the support payments and the value of the generated electricity. The grid operators have to buy the electricity generated by renewable energy sources at a fixed feed-in tariff. The electricity generated by renewable energy sources is sold to the suppliers as a monthly base load block at the price of the average feed-in tariff. Important aspects for the analysis of the support scheme are the actual value of the electricity that is bought by the grid operators and the value of the base load block that is sold to the supply companies. In order to assess the value of the generated electricity, the market price on the German spot market EEX seems to be a good indicator since spot market prices form the most important price information that is available in public. But it has to be stated that a considerable volume of the electricity is traded in bilateral contracts. Since the prices of these contracts are unknown, there is some uncertainty whether these contracts have prices which deviate from spot market prices. As spot market prices vary on hourly level, the assessment of the market value should be carried out on the same timescale. For the analysis of the market value the hourly load profiles for renewable electricity generation described in Chapter 5 are multiplied with the corresponding market price in the given hour. Due to the availability of detailed data on the electricity generation by wind energy the analysis is carried out for the years 2001, 2004, 2005 and 2006. An overview of the results of the analysis and a comparison with the average market price of a base load block are given in Figure 6-1. The figure shows a heavy increase of market prices in the given period. Possible explanations for the heavy increase in prices are higher fuel prices and the introduction of the European emission trading system. Another important result is that the value of the renewable electricity generation is close to the value of the base load block that is passed on to the suppliers. In the later years 2005 and 2006 the calculated value of the renewable electricity generation is slightly lower than the average market price.

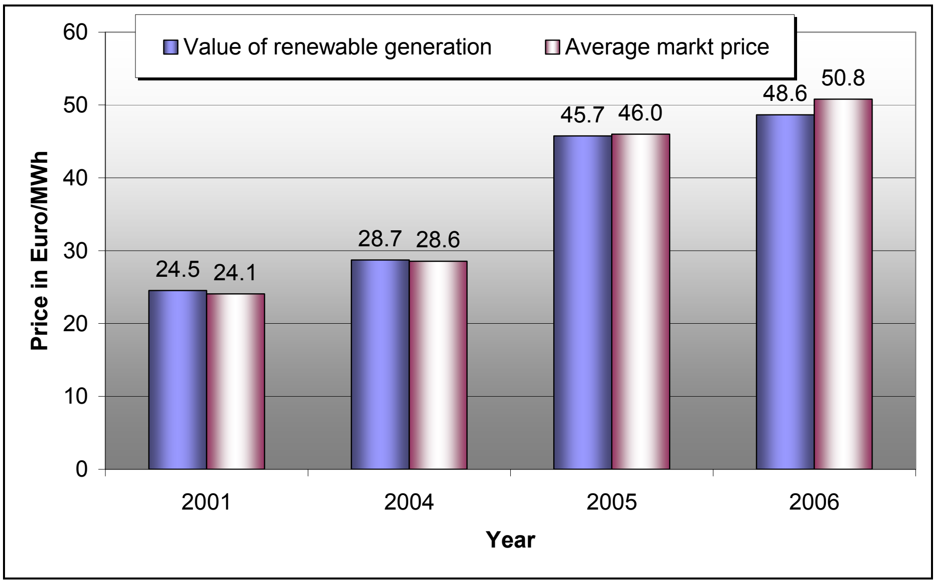


Figure 6-1: Comparison of the average market price and the calculated value of renewable electricity generation based on EEX prices

Source: own illustration, market prices based on European Energy Exchange [EEX] (2006a-e); European Energy Exchange [EEX] (2007e)

An interesting question in this context is whether the value of the electricity generated by the different renewable energy sources varies due to their different load profiles. Based on the load profiles integrated into the PowerACE Cluster System, the analysis of the market value can also be carried out on technology level. The results of the analysis of the market value for the year 2006 are presented in Figure 6-2. The average market price and the calculated average market value of renewable electricity generation are presented for a better comparison.

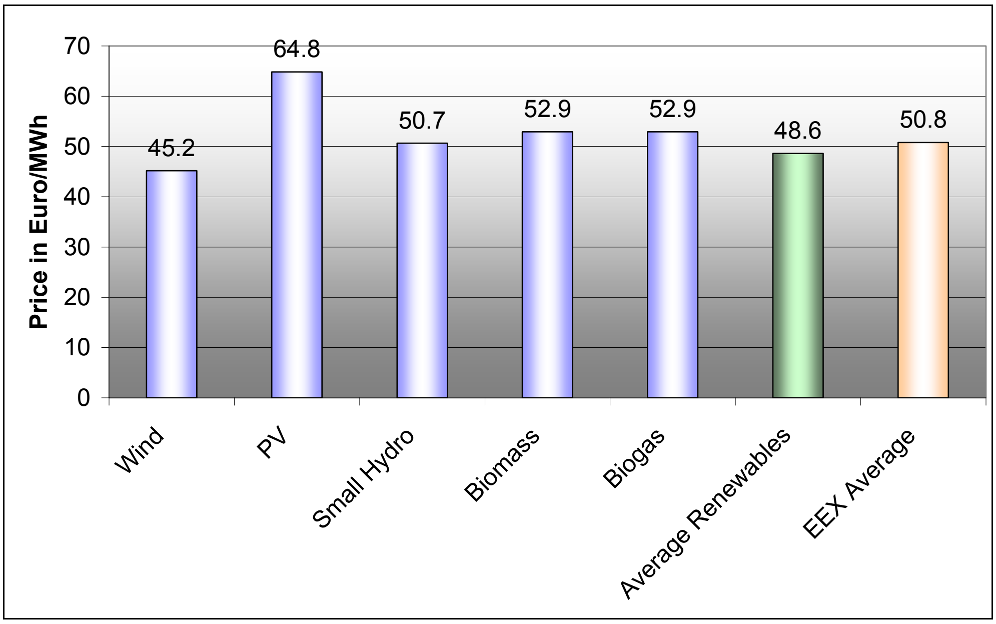


Figure 6-2: Comparison of the calculated market value for the year 2006

Source: own illustration, market prices: (European Energy Exchange, 2007e)

The analysis shows considerable differences in the market value of the different technologies. These differences are caused by the different shape of the load profile of the renewable technologies. Wind energy reaches the lowest value of 45.2 Euro/MWh. Photovoltaic (PV) reaches the highest value with 64.8 Euro/MWh due to the higher share of electricity generation in the peak hours around noon. As hydro power plants have no daytime variations in their load profile, the market value is almost identical with the average market price. A slightly higher market value is reached for the electricity generated by biomass and biogas. This is mainly caused by the fact that the synthetic load profile applied for biomass plants is assumed to follow the heat demand which is higher in daytime. Since data on the actual utilization and load profile of these plants is not available, it has to be taken into account that there is some uncertainty in the calculation of the market value of biomass plants. Since the load profile of PV and small hydro plants is based on the meteorological data of years other than 2006, there is also a minor uncertainty concerning the calculation of the market value. But as the main characteristics in terms of the daily profile do not change over the years, the calculation should still be very close to the real world situation.

Another interesting aspect for the analysis is the question whether the value of the electricity generated by the single technologies changes over time. As the electricity prices have changed heavily in the period 2001-2006; it seems to be more promising to analyse the relative changes of the value of the electricity generation by the different technologies if the value is compared to the average market price. Therefore the value of the electricity generated by renewable energy sources is divided by the market price of the given year in the analysed years 2001, 2004, 2005 and 2006. In order to get an impression of the annual variations in the relative value of the generated electricity; the minimum, maximum, and the average ratio of renewable electricity generation and the market price are calculated. The comparison given in Figure 6-3 shows that for most technologies the relative value can vary by about 10 %. The variation of the relative value of renewable electricity generation reaches 6 %.

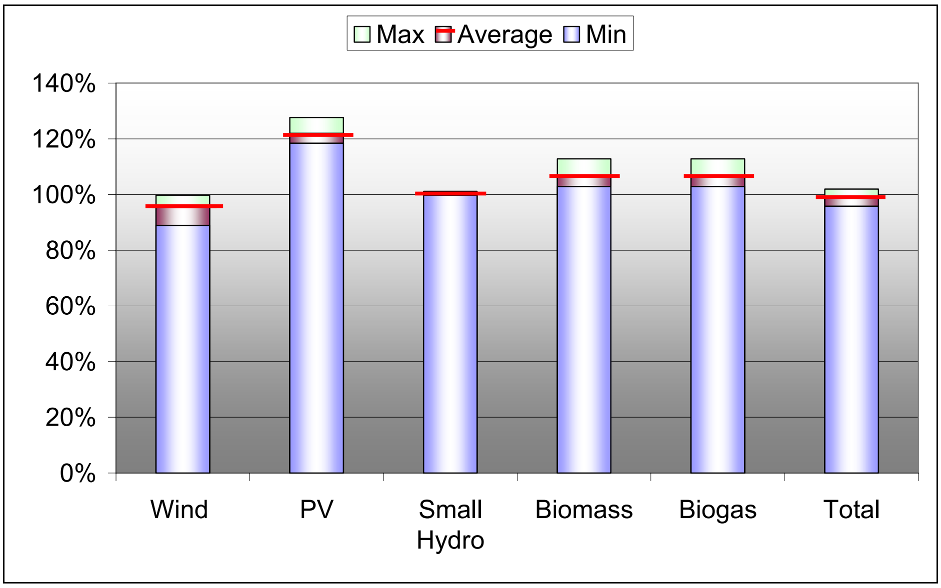


Figure 6-3: Range of the relative value of renewable electricity generation in the analysed period

Source: own illustration

The final steps in the analysis are the calculation of the absolute volume of the support payments and the net support as the difference between support payments and value of renewable electricity generation. The German Association of grid-operators [VDN] published data on the volume of the supported electricity generation and the average feed-in tariff (Verband der Netzbetreiber [VDN], 2007a). These values form the basis for the calculation of the support scheme. It has to be stated that the published data may vary slightly from the real electricity generation due to the accounting procedures of the VDN. A comparison of the main indicators of support and volume of renewable electricity generation is given in Table 6-1. The data shows a remarkable increase in the support payments from ca. 1.6 billion Euro to 5.38 billion Euro in the year 2006. Due to the heavy increase in market prices the value of renewable electricity generation rose even faster from 0.45 billion Euro to 2.54 billion Euro. Therefore the net support rose more slowly from 1.13 to 2.84 billion Euro. The specific net support of renewable electricity generation is reduced from 62.4 Euro/MWh to 54.4 Euro/MWh in 2006.

Table 6-1: Main indicators of the value of renewable electricity generation

Year	Electricity generation TWh	Average support €/MWh	Value €/MWh	Support payments Billion €	Value Billion €	Specific net support €/MWh	Net support Billion €
2001	18.1	86.9	24.5	1.58	0.45	62.4	1.13
2004	38.5	92.9	28.7	3.58	1.11	64.2	2.47
2005	44.0	100	45.7	4.40	2.01	54.3	2.39
2006	52.2*	103	48.6	5.38	2.54	54.4	2.84

Sources: Average support payments and electricity generation are based on (Verband der Netzbetreiber [VDN], 2007d) ;* Electricity generation and volume of the support payments in 2006 are based on own calculations considering the more detailed dataset (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, 2007a). The resulting electricity generation is 1.9 TWh higher than the data published by the VDN.

Due to the considerable volume in financial terms these figures play an important role in the analysis of the impact of the renewable support schemes on different players in the electricity sector.

6.1.2 Merit-order effect

In addition to the value of the electricity generated by renewable energy sources the supported electricity generation also has an impact on the market price itself. The main goal of this section is the analysis of this interaction. An overview of the discussed effects of renewable electricity generation is given in Figure 6-4 for a single hour. It is assumed that the electricity demand is inelastic in the short-term perspective of a day-ahead market. Since the electricity generated by renewable energy sources has to be bought by supply companies in advance, the remaining demand load that has to be purchased on the electricity markets is reduced correspondingly. Therefore, the guaranteed feed-in of electricity generated by renewable energy sources has the effect of a reduced electricity demand. In the diagram the German merit-order curve is depicted as a step function. As long as this supply curve has a positive slope, the reduced demand on the markets leads to lower prices. As this effect shifts market prices along the German merit-order of power plants, this effect is called the "merit-order effect" in this thesis. A central goal of this section is to assess the actual value of the merit-order effect of German renewable electricity generation in the year 2006.

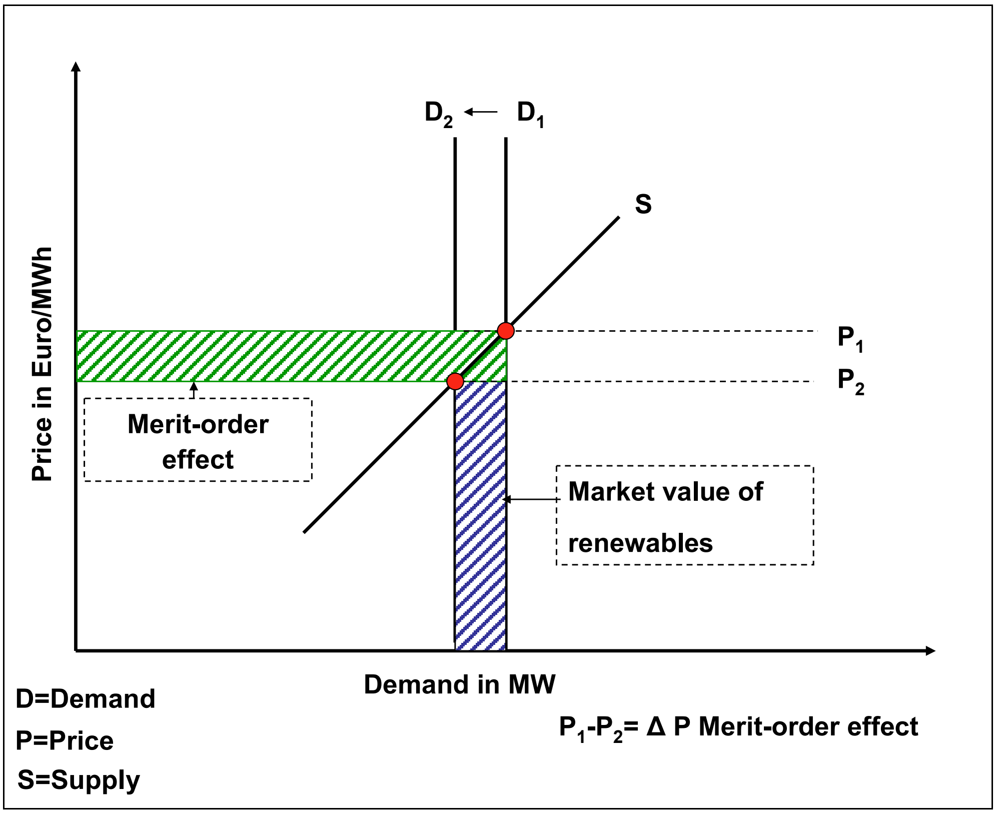


Figure 6-4: Merit-order effect of renewable electricity generation
Source: own illustration

Since electricity demand and renewable electricity generation vary on an hourly basis, an estimation of the actual value of the merit-order effect is far more complex than the estimation of the market value. Therefore the analysis is carried out using the PowerACE Cluster System which is able to simulate hourly spot market prices. An important assumption in this context is that the spot market represents the leading price indicator for all electricity trades. Possible interactions with the market for electricity futures and the bilateral market cannot be taken into account. Since the simulation of spot market prices is based on fundamental cost data leading to a lower volatility than the real world markets, the assumption that the simulated spot market price is the leading price indicator seems to be adequate.

6.1.2.1 Results

In order to determine the impact of renewable electricity generation, the calibrated model is used to simulate electricity market prices in the years 2001 and 2004-2006. Thereby it is assumed that the entire electricity demand is traded at the simulated spot market. This assumption deviates form the real wolrd situation in two ways:

1. In the real world situation only ca. 89 TWh or 16.5 % of the electricity demand were traded on the spot market in 2006 (European Energy Exchange [EEX], 2007f). It can be assumed that an important amount of electricity is traded in bilateral contracts which are likely to be less volatile than the spot market.
2. The simulated spot market prices are based on fundamental data. Therefore prices are less volatile than real world market prices (also see Chapter 5.4.1) It is not likely that peak prices of several hundred Euro/MWh at the real spot market represent a good price signal for the entire electricity demand in a given hour. Under the given assumption that the entire electricity demand is traded at the resulting market prices it seems to be adequate to base the analysis on the more conservative price development of the simulated market prices.

In case of renewable electricity generation the electricity generation is calculated based on given hourly load profiles. The resulting electricity production may differ from published production data due to the fact that the capacity available at the end of the year is assumed to be producing for the entire year according to the technology specific utilization.

All other parameters are held constant. In order to determine the impact of renewable electricity generation on the electricity market the simulation is run 50 times. The resulting time series is calculated as average of the simulation runs in order to level out variations caused by the random generator used to simulate power plant outages. In a second step the same procedure is applied to 50 simulation runs without renewable electricity production supported by the feed-in tariff. Since the development of large hydro plants has not yet been affected by the renewable support scheme, electricity production of large hydro plants is taken into account in both simulation settings. The following analysis compares both time series. A comparison of a selected day in October 2006 is given in Figure 6-5. The figure shows the impact of renewable electricity generation supported by the EEG on the remaining system load that has to be covered by conventional power plants. The load of renewable electricity generation in the selected period varies between 4.4 GW and 14.7 GW. But its impact on prices varies even more. During hours of low load the reduction of the market price is 0 Euro/MWh while it reaches up to 36 Euro/MWh in hours of peak demand. This difference in the impact on market prices is caused by the different slope or step size of the German merit-order curve in different load segments of the electricity demand. The slope of the German merit-order is higher in cases of high demand. This effect is illustrated in a stylized way in Figure 6-6.

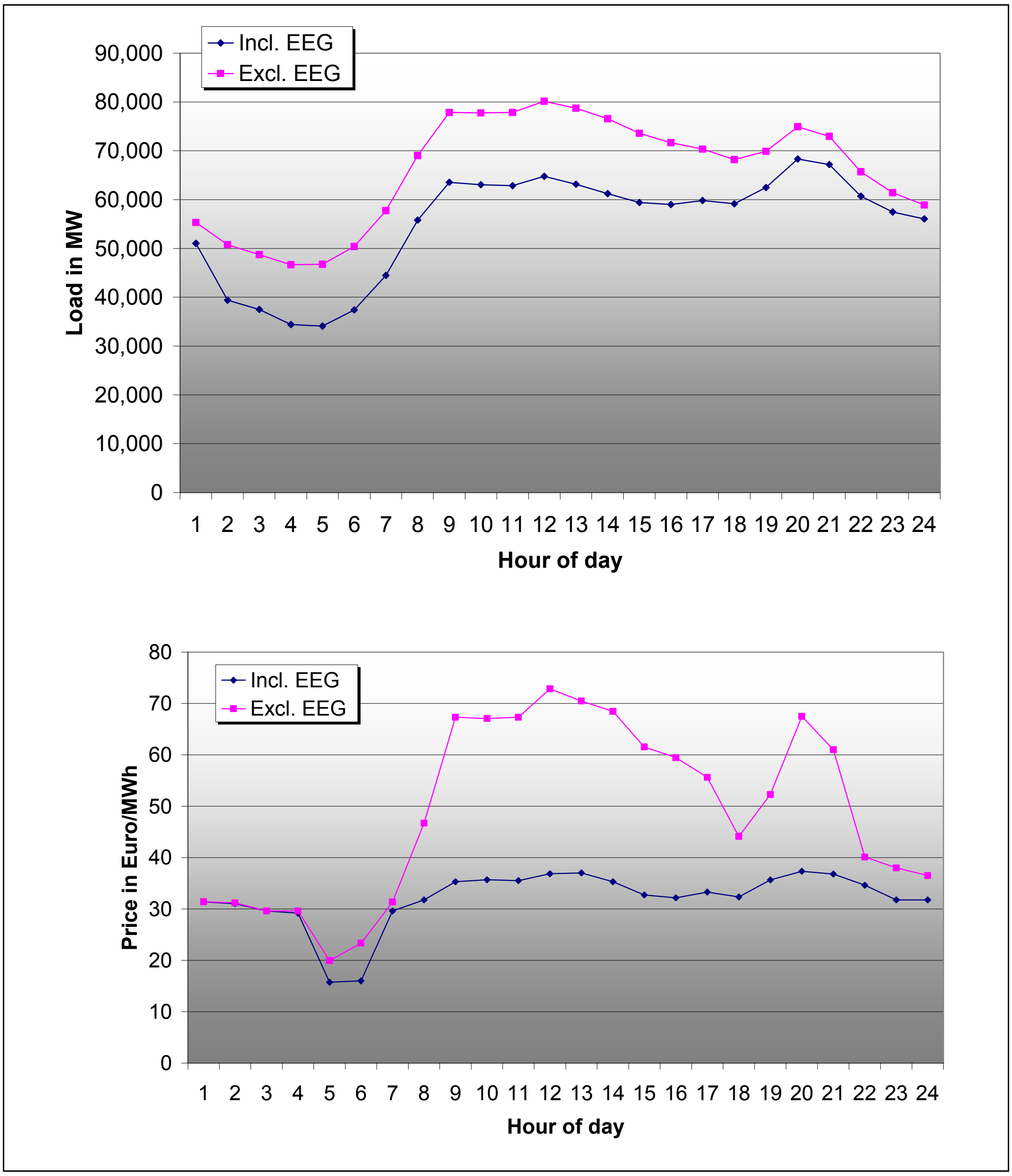


Figure 6-5: Comparison of load and prices for one simulated day in October 2006 (two scenarios: one including EEG-Renewables, the other excluding EEG-Renewables)

Source: own illustration

Based on the assumption that the entire electricity demand of a single hour is purchased at the corresponding spot market price the volume of the merit-order effect can be calculated. If the difference is summed up according to Formula 6-1, the absolute volume of the merit-order effect can be estimated.

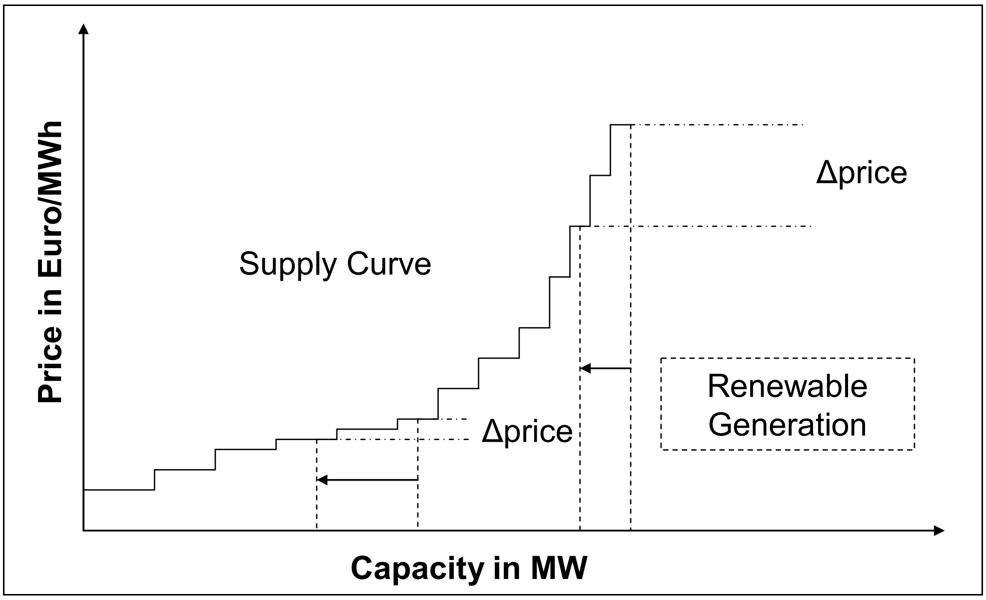


Figure 6-6: The impact of renewable generation on market prices in different segments on electricity demand

Source: own illustration

Formula 6-1: Calculation of the annual financial volume of the "merit-order effect"

$$v = \sum_{h=1}^{h=8760} (x_h - p_h) \cdot d_h$$

Legend:

Variables			**Unit**	**Indices**
d	=	Total electricity demand	[MWh]	h = Hour
p	=	Price including renewable generation	[Euro/MWh]	
x	=	Price excluding renewable generation	[Euro/MWh]	
v	=	Total volume of the merit-order effect	[Euro]	

The results for the years 2001, 2004, 2005 and 2006 are presented in Table 6-2. The results indicate a considerable reduction of the average market price of 7.83 Euro/MWh in the year 2006. In total the volume of the merit-order effect reaches its highest value in the year 2006 with about 4.98 billion Euro. Another interesting indicator for the discussion of the actual cost of renewable electricity support from the consumer perspective is the ratio of the merit-order effect and the electricity generated by renewable energy sources (Formula 6-2). This indicator allows a comparison to the average specific tariff for renewable electricity of 103 Euro/MWh in 2006 (Verband der Netzbetreiber [VDN], 2007d). This indicator reaches 95.4 Euro/MWh in the year 2006.

Formula 6-2: Calculation of the specific value of the merit-order effect

$$s = \frac{v}{r}$$

Legend:

Variables			Unit	Indices
r	=	Renewable electricity generation	[MWh]	
s	=	Specific value of the merit-order effect	[Euro/MWh]	
v	=	Volume of the merit-order effect	[Euro]	

Table 6-2: Price-effect and total volume of the merit-order effect[9]

Year	Simulated renewable generation TWh	Average price reduction €/MWh	Volume merit-order effect Billion €	Merit-order effect per renewable MWh €/MWh	Average feed-in tariff €/MWh
2001	24.3	1.7	1.07	44	86.9
2004	41.5	2.5	1.65	40	92.9
2005*	45.5	4.25	2.78	61	99.5
2006	52.2	7.83	4.98	95	103

* In order to ensure a consistent procedure, the values for the year 2005 are calculated excluding the scarcity mark-up presented in Chapter 5.3.7. If the scarcity mark-up is included, the merit-order effect in the year 2005 is higher (also see Chapter 6.1.2.2.3).

6.1.2.2 Sensitivity analysis

An analysis of the development of the volume of the merit-order effect shows that the effect is not only influenced by the growth of renewable electricity generation. The main driving factors for the level of the merit-order effect are the installed capacity of renewable electricity generation, the development of fuel prices and the CO_2 price. In total 42 scenarios with 50 simulation runs are carried out for the sensitivity analysis of the year 2006. The total amount of 2100 simulation runs leads to extensive requirements in terms of computing power, data handling and data storage since the produced data for this analysis amounts to ca. 20 GB.

6.1.2.2.1 Fuel prices

In order to analyse the impact of changes to the fuel prices, the merit-order effect is determined for simulation runs with different fuel prices. Thereby simulations are run with a price increase and decrease of 20 % for each fuel and a general variation of prices by 20 % for all fuels. The results are shown in Table 6-3. The first step is a general variation of +-20 % on all prices. The variation has almost the same corresponding effect on the volume of the merit-order effect.

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9 The volume of the renewable electricity generation deviates slightly from the published data by the (see also Table 6-1). This effect is caused by the fact that the model settings assume that the renewable electricity generation capacity at the end of a year is available for the entire year.

Table 6-3: Sensitivity Analysis for the year 2006

2006	**Fuel prices**			**Relative change merit-order effect**	
	low €/MWh	**normal** €/MWh	**high** €/MWh	**low** %	**high** %
Nuclear	2.99	3.75	4.49	0	0
Hard coal	6.37	7.98	9.55	11	-9
Lignite	3.03	3.79	4.55	2	-1
Oil	25.65	32.15	38.48	-2	1
Gas	17.30	21.69	25.95	-30	26
All	-20 %	0	20 %	-20	18

The sensitivity analysis for the year 2006 shows that the fuel prices for lignite and nuclear power plants only have a very low impact on the value of the merit-order effect. Despite the spread of +/- 20 % in the fuel cost the fuel price only influences the value of the merit-order effect by a maximum of 2 %. This result is not surprising as the base load power plants are largely unaffected by the development of renewable electricity generation up to 2006 due to the fact that they are rarely replaced by renewable electricity generation.

In case of fuel oil the sensitivity analysis for fuel oil shows only a very low impact on the value of the merit-order effect. A 20 % lower fuel price decreases the value of the merit-order effect by 2 % while the higher oil price increases the merit-order effect by 1 %. The low sensitivity can be explained by the low importance of oil fired power plants in the German electricity supply. Since the number of plants is low, they only set the market price in rare cases.

The analysis of the variation of the gas price shows the highest impact on the result. A reduction of the gas price by 20 % leads to a reduction change of the merit-order effect of ca. 30 %. The disproportionately high effect of a variation of the gas price on the volume of the merit-order effect can be explained by the impact of the gas price on the generation cost. The gas turbines for peak demand have a lower efficiency, which makes the generation cost more sensitive towards higher fuel prices. Since gas fired units set the prices in most hours of peak demand, the effect is not levelled out by scheduling another generation technology.

Another important factor with an influence on the result is the hard coal price. A 20 % variation of the fuel price leads to an opposite effect of 9 % and 11 % on the volume of the merit-order effect. At first sight this result is striking, but the analysis shows that the result is not only influenced by a single fuel price or the general price level of fuel prices. An important factor influencing the results is the ratio of gas and coal prices.

The strong dependency of the effect to the ratio gas and coal prices can be explained by the German merit-order curve. Price setting units are mostly coal and gas power plants. In hours of lower electricity demand the price is set by hard coal units and in hours of high demand the price is set by gas units. Therefore higher hard coal prices reduce the slope of the merit-order curve, thus reducing the merit-order effect. Very high coal prices and lower gas prices decrease the slope of the supply as depicted in Figure 6-7.

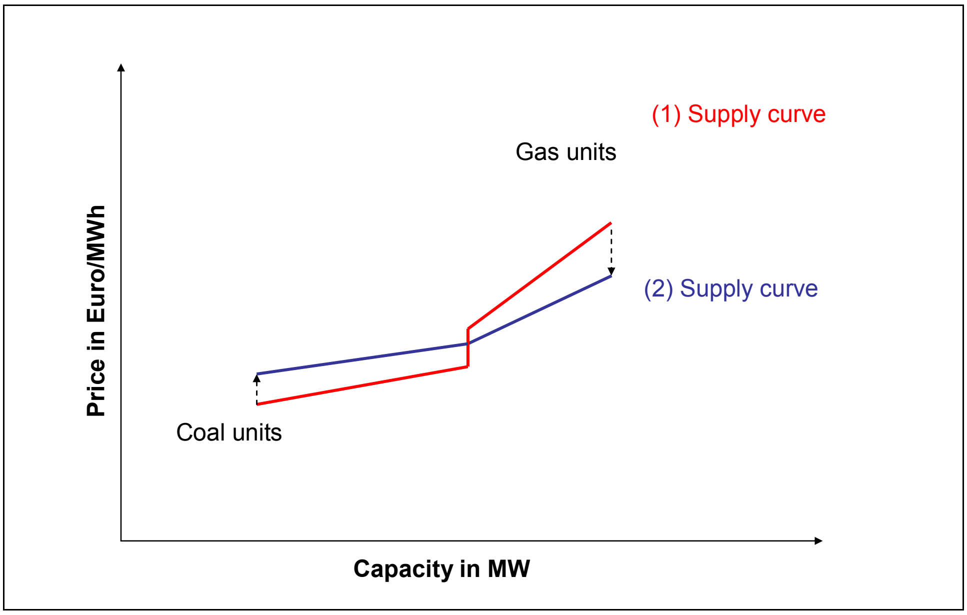

Figure 6-7: The impact of coal and gas prices on the supply curve
Source: own illustration

6.1.2.2.2 Capacity

In addition to the fuel prices the factor that has an obvious impact on the volume of the merit-order effect is the amount of electricity generated by renewable energy sources. In order to determine the impact of this factor all parameters of the simulation run for the year 2006 are held constant while the supported renewable electricity generation capacity is varied in steps of 20 %. The results presented in Table 6-4 show that the merit-order effect grows almost in line with renewable electricity generation. While the supported renewable electricity generation grows by 40 % from 52.2 TWh to 73.1 TWh in the analysed simulation, the volume of the merit-order effect grows by 31 %. In the given setting there is a tendency that the growth rates of the merit-order effect decrease slightly with increasing renewable electricity generation. This is again caused by the slope of the German merit-order curve which decreases with lower load. Thereby it has to be taken into account that the sensitivity analysis of fuel prices presented above shows that the actual slope of the German merit-order curve is influenced heavily by fuel prices, which again influences the sensitivity of the simulation results towards the volume of renewable electricity generation.

Table 6-4: Impact of growing renewable electricity generation on the merit-order effect

Renewable Generation TWh	RES-Generation Comparison to 2006	Effect Comparison to 2006
31.3	60 %	66 %
41.8	80 %	86 %
52.2	100 %	100 %
62.6	120 %	118 %
73.1	140 %	131 %

6.1.2.2.3 Scarcity mark-up

Another factor which has an impact on the result of the merit-order effect is the scarcity mark-up. In case of the year 2005 the scarcity mark-up is added to the bid price jn order to get a more realistic representation of EEX prices. As renewable electricity generation also affects the scarcity of generation capacity in a given hour, the merit-order effect is also influenced by the scarcity mark-up. In order to determine the impact of the scarcity mark-up the calculation of the merit-order effect is carried out with activated and deactivated mark-up for the years 2005 and 2006. The results presented in Table 6-5 show that the mark-up increases the merit-order effect by ca. 0.6 and 0.7 billlion Euro for the years 2005 and 2006. As the impact of the scarcity mark-up is considerable, this aspect clearly needs further investigation. But as there is no broad empirical validation available, it is not applied for the analysis carried out in this thesis.

Table 6-5: Sensitivity analysis of the scarcity mark-up

Year	Simulated renewable generation TWh	Volume merit-order effect no mark-up Billion €	Volume merit-order effect incl. mark-up Billion €	Difference Billion €	Relative Change %
2005	45.5	2.78	3.41	0.63	23
2006	52.2	4.98	5.69	0.71	14

6.1.2.2.4 CO_2 prices

Another important parameter is the CO_2 price. In order to calculate the sensitivity of the results to the CO_2 price the merit-order effect is simulated with the PowerACE Cluster System with varying CO_2 prices. The CO_2 prices are varied between 0 Euro/t and 40 Euro/t in steps of 10 Euro/t. The results are presented in Table 6-6. The results indicate that the volume of the merit-order effect decreases slightly with increasing CO_2 price. A rise of the daily CO_2 price from 0 to 40 Euro/t leads to a reduction of the merit-order effect by ca. 16 %.

Table 6-6: Impact of CO_2 prices on the merit-order effect

CO_2 prices (€/t)	**Relative change** (%)
0	0
10	-4
20	-8
30	-12
40	-16

At first sight this result is rather surprising. In order to illustrate the effects caused by rising CO_2 prices the merit-order curve of a small power plant portfolio is created for illustration purposes. The plant portfolio consists of eleven hard coal and gas fired power plants with different efficiencies. The characteristics and the merit-order curve of this simplified power system for different CO_2 prices are given in Table 6-7 and Figure 6-8.

Table 6-7: Simplified power plant portfolio

Fuel	**Capacity** MW	**Efficiency** %	**Fuel Price** €/MWh	**Variable cost** €/MWh	**Generation cost** €/MWh
Hard coal	1	44	8.4	1.5	20.6
Hard coal	1	42	8.4	1.5	21.5
Hard coal	1	41	8.4	1.5	22.0
Hard coal	1	40	8.4	1.5	22.5
Hard coal	1	35	8.4	1.5	25.5
Gas	1	58	16.4	0.5	28.8
Gas	1	50	16.4	0.5	33.3
Gas	1	35	16.4	0.5	47.4
Gas	1	34	16.4	0.5	48.7
Gas	1	33	16.4	0.5	50.2
Gas	1	32	16.4	0.5	51.8

Figure 6-8 shows increasing prices with increasing CO_2 prices and differences in the slope of the merit-order curve. Since the slope of the merit-order curve is the most important parameter that determines the volume of the merit-order effect, another figure is added which analyses the slope of the merit-order curve in different segments with varying CO_2 prices. The result is presented in Figure 6-9. The figure shows that there are two different effects changing the slope of the merit-order curve. Within a certain technology group like gas turbines the increasing CO_2 prices increase the slope of the merit-order curve since the impact of efficiencies on generation cost increases. This effect should increase the merit-order effect of renewable electricity generation. Another important aspect which seems to have a stronger impact is the fuel switch effect. Higher CO_2 prices move hard coal power plants up within the merit-order curve, thereby decreasing the slope of the shoulder and peak load segment. As the result the volume of the merit-order effect decreases. The actual size of both effects heavily depends on the position within the merit-order curve which is determined by the hourly renewable electricity generation and the total electricity demand. In addition it has to be stated that the actual size of both effects heavily depends on the relation of gas and coal prices and the CO_2 price. In summary this simplified analysis shows the complexity of the effects determining the impact of CO_2 prices on the merit-order effect. Thereby the detailed PowerACE simulation helps to determine the volume of the discussed effects which are almost impossible to estimate at first sight.

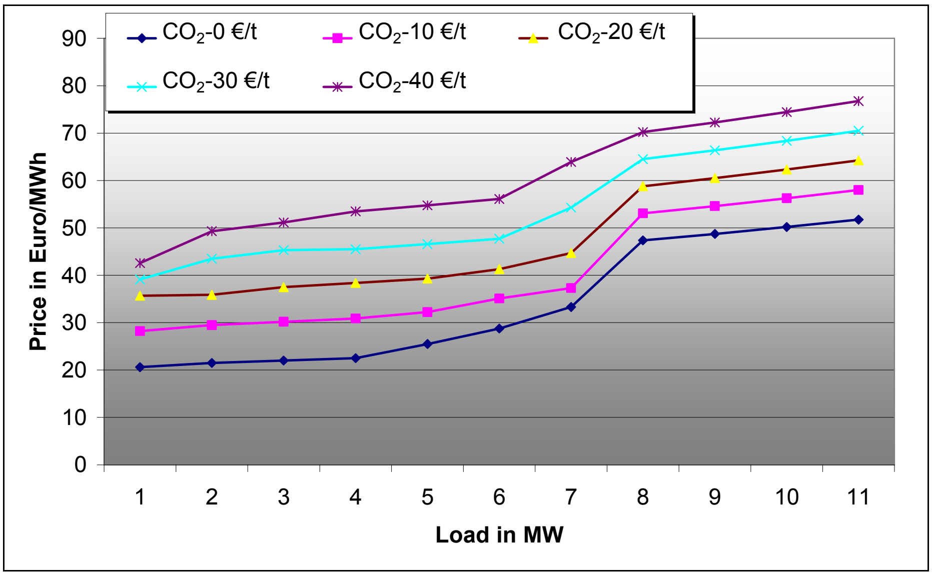

Figure 6-8: Merit-order curve of the simplified power system

Source: own illustration

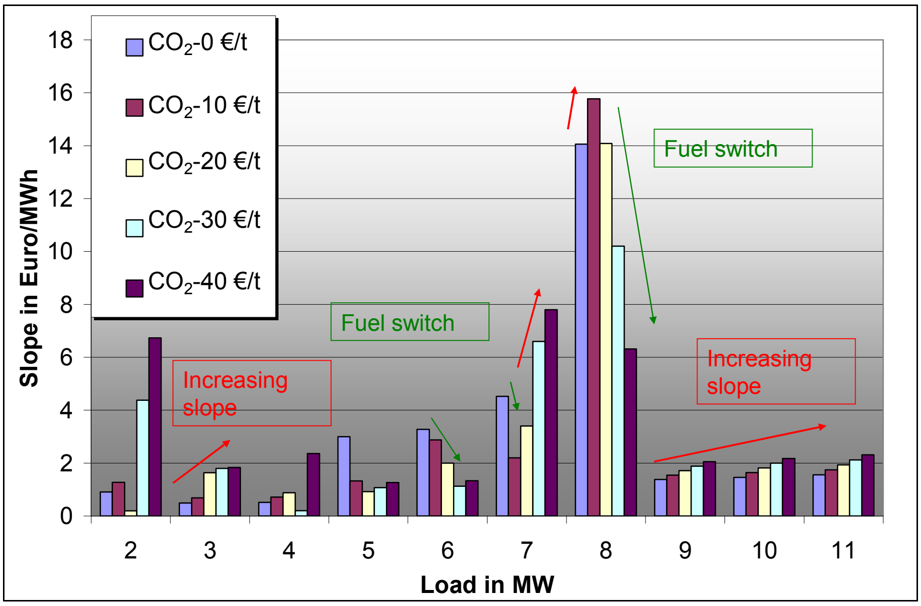

Figure 6-9: Slope of the merit-order curve

Source: own illustration

6.1.2.3 Comparison with the literature

There are some studies which have been carried out in order to estimate the effect of renewable electricity generation on German spot market prices. Neubarth et al. (Neubarth et al., 2006) try to assess the value of the trades carried out by the grid operators in order to deal with fluctuating wind energy. They apply statistical methods to the analysis of a time series of spot market prices and day-ahead wind prognoses. The analysed time period is 01.09.2004-31.08.2005. They determine an average price effect on the daily average price of 1.89 Euro/MWh per GW average available wind energy. By scaling this effect to an installed capacity of 18.4 GW for the year 2005 and the corresponding wind conditions a value of 6.08 Euro/MW is reached. However the PowerACE results with considerable differences in the results between 2004 and 2005 show that the selected time period for the statistical analysis may not be a good choice. In addition the analysis carried out by Neubarth et al. neglects important factors such as plant outages, CO_2 prices, load and fuel prices. In case of correlation between one of these factors and the wind energy production the estimation could be changed heavily. Another approach is presented by Bode and Groscurth (Bode and Groscurth, 2006). They apply an approach which is in principle similar to the approach of this thesis. Based on a rather simple representation of the electricity sector they estimate an average price effect of 2.4 Euro/MWh in case of 36.7 TWh electricity generation and a CO_2 price of 0 Euro/t. In a next step they vary the amount of renewable electricity generation in case of elastic and inelastic demand. As a result an average impact of 0.55 Euro/MWh or 0.61 Euro/MWh per GW available renewable electricity capacity is estimated. The upscaling of this effect to the simulated electricity generation in PowerACE of the year 2005 with an average renewable electricity generation of 45.5 TWh leads to an effect of 3.17 Euro/MWh. In another paper Bode (Bode, 2006) applies the results to the analysis of the price effects of different support schemes. The assumed slope of the supply curve is varied without new empirical analysis. In Table 6-8 the results of the discussed studies for Germany are compared to the analysis carried out with the PowerACE Cluster System[10].

Table 6-8: Comparison of the results for the merit-order effect

	Own calculations	**Own calculations**	**Own calculations**	**Bode, Groscurth 2006**	**Neubarth et al. 2006**
Time period	2004	2005	2006	Model period	2004-2005
Approach	PowerACE model	PowerACE model	PowerACE model	Simple model	Statistical approach
Price Effect	2.5 €/MWh	4.25 €/MWh	7.83€/MWh	3.17 €/MWh	6.08 €/MWh

10 Due to the calibration procedure described in the previous Chapter the settings of the PowerACE Cluster System deviate for the different years with regard to the settings of the CO_2 price factors and the scarcity mark-up. (2004 includes no scarcity mark-up and no CO_2 prices, 2005: CO_2 price factors: Gas 100 %, Hard coal 85 %, Lignite 70 %; 2006 no scarcity mark-up included, CO_2 price factors: Gas 100 %, Hard coal 100 % Lignite 20 %.)

Table 6-9: Comparison of the main characteristics of the approaches applied for the period 2004-2005

Category	**Own calculations**	**Bode, Groscurth 2006**
Method	PowerACE model	Model/estimation
Power plant portfolio	Database (Actual-Stock) > 1,200 power plants	Synthetic power plant portfolio (200 power plants)
Electricity demand	556 TWh (UCTE 2005)	500 TWh
Load curve	ISI Load Model Hourly curve for the entire year Basis: Temperatures of 2005	Hourly curves for 12 days (UCTE 2002)
Demand	Inelastic	Elastic, inelastic
Renewable load	Wind: • ISI-Windmodel 2001 • ISET-SEPCAMO 2004 Wind-prognosis • ISET-SEPCAMO 2005 Wind-prognosis PV, Biomass: ISI Models	Random generator
CO_2 price	Actual EEX Prices of 2005	Constant: zero
Fuel prices	Average Prices 2005: Coal: 8,39 Euro/MWh Gas: 16,43 Euro/MWh Lignite: 3,8 Euro/MWh Oil: 25,91 Euro/MWh (Enzensberger, 2003; Bundesamt für Wirtschaft und Ausfuhrkon-trolle, 2006a; Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2006b)	Synthetic prices Coal: 6 Euro/MWh Gas: 14 Euro/MWh
Reserve markets	Primary reserve Secondary reserve Tertiary reserve	Not included
Pump storage	Dynamic utilization	Not included
Power plant outages	Nuclear: Based on published elec-tricity generation data Others: Calibrated Random genera-tor	Not included
Sensitivity analysis	42-Scenarios: Varied Fuel Prices Varied CO_2 prices Varied renewable capacity	(Renewable electricity generation)

The value published by Bode and Groscurth is considerably lower than the PowerACE results for the year 2005 and a bit higher than the results for the year 2004. The sensitivity analysis carried out in PowerACE shows that the merit-order effect is very sensitive to fuel prices and other assumptions, such as renewable electricity generation and fuel prices. Therefore the differences can be explained by the underlying assumptions. The applied fuel prices of Bode and Groscurth are considerably lower than the import prices of the year 2005. In general the approach of Bode is far less detailed than the PowerACE model. An outstanding example is that PowerACE simulates realistic load profiles and market prices for an entire year (8760 hours) while the model by Bode et al. simulates only for 12 days. An overview of the main characteristics and differences is given in Table 6-9.

6.1.3 Impact on the CO_2 market

Another important aspect of renewable electricity generation is the impact on the CO_2 market. A first step is the assessment of the CO_2 savings caused by renewable electricity generation. The CO_2 savings are achieved because renewable electricity generation replaces electricity generated by fossil fired power plants. The electricity generation by renewable energy sources reduces the demand on the market for European CO_2 emission allowances [EUA]. As long as the supply curve has a positive slope, this reduction in demand leads to a reduction of CO_2 prices. The actual price effect depends on the amount of CO_2 savings created by renewable energy sources and the slope of the supply and the demand curve. An overview of the discussed effect is given in Figure 6-10.

The value of the CO_2 savings on the CO_2 market can be approximately estimated by multiplying the volume of the savings with the average market price of the corresponding year. The reduction of prices on the CO_2 market creates savings for all sectors that take part in the European emission trading system. In case of free allocation of emission rights this effect also leads to a reduction of profits as the value of the freely allocated emission rights is reduced. As the central goal of this thesis is to analyse the impact of renewable electricity generation on the electricity sector, the present analysis also focuses on the impact of the created CO_2 savings on the electricity sector. Since the CO_2 price is part of the variable cost of power plants a lower market price on the CO_2 market leads to lower variable cost of fossil fuel fired power plants. This effect shifts the supply curve on the electricity market downward. Since the CO_2 price has a stronger impact on the CO_2 intensive power plants, the slope of the supply curve also changes. An overview of the discussed effects is given in Figure 6-11. The downward shift of the supply curve leads to a reduction of the electricity price from P_1 to P_2. Since this price reduction reduces the market price for the entire demand traded in the given hour, an effect similar to the merit-order effect is created. The described effect is also discussed in the literature (Rathmann, 2007, Walz, 2005, p.266).

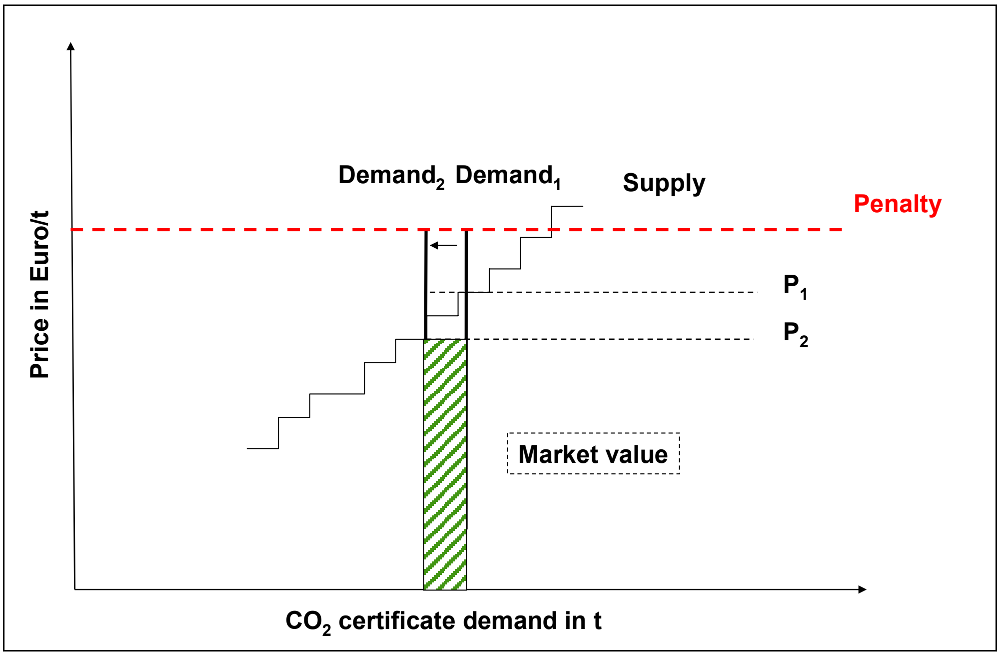

Figure 6-10: Impact of renewable electricity generation on CO_2 prices
Source: own illustration

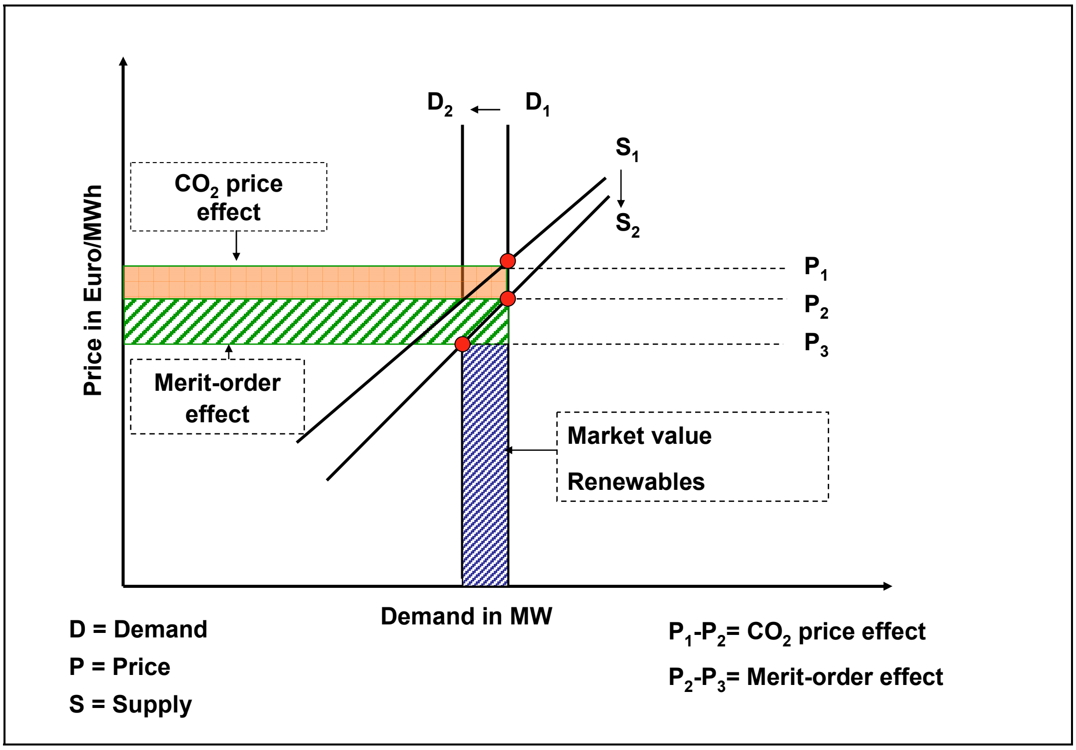

Figure 6-11: CO_2 price effect of renewable electricity generation on the electricity market
Source: own illustration

The quantification of this effect is a very complex task. The first step is to determine the CO_2 savings brought about by renewable electricity generation. In a second step the costs of alternative saving options need to be determined in order to assess the potential impact of the created savings on the CO_2 prices in the CO_2 market. In order to provide an assessment of the potential impact of the CO_2 savings created by renewable electricity generation a number of assumptions concerning the framework conditions have to be made.

1. It is assumed that the CO_2 savings that are now created by renewable electricity generation would have to be created within the electricity sector by physical savings or the purchase of additional emission allowances. In other words it is assumed that the allocation of emission allowances in the allocation plan remains unchanged, which is a very strong assumption. It is possible that the allocation plan and especially the distribution of emission targets of sectors included in the emission trading scheme and those sectors not included in the emission trading scheme would be different without the supported renewable electricity generation.
2. The costs of saving measures within sectors not participating in the emission trading system are not integrated into the analysis since they do not affect market prices within the emission trading system. But it has to be stated that in the long run measures concerning transport or buildings may provide a considerable volume of CO_2 savings at low cost (see also Intergovernmental Panel on Climate Change [IPCC], 2007).
3. The total CO_2 emissions in Europe are held constant, which means that the created CO_2 savings cannot be replaced by excess emission allowances due to the generous allocation of emission allowances in the first trading period. This is a strong assumption in the first trading period since the market in the year 2006 is characterized with an excess of emission rights. The excess emission of rights is higher than the magnitude of the CO_2 savings created by renewable electricity generation in Germany (Ellerman and Buchner, 2007). Due to the less generous allocation in the second period this issue is likely to disappear.
4. Side effects of allocation rules which can create additional profits for new plants or the operation of older plants cannot be taken into account for the assessment of alternative saving options due to the complexity of the situation.

In a last step the impact of the reduced CO_2 prices on market prices in the electricity sector needs to be determined. An example for the quantification of the effect can be found in the literature. Rathmann estimates that the supported renewable electricity generation in Germany of the years 2005-2007 reduces the price for CO_2 allowances by 5.4 Euro/t (Rathmann, 2007, p.347). However, the assumed short position of the CO_2 market turned out to be wrong. Since the entire calculation is based on this assumption, the given estimation does not reflect the real situation. The following figure shows the development of the daily European Emission Allowance [EUA] price in the period between March 2005 and the end of 2006. The figure shows the development of EUA prices. While CO_2 prices in the year 2005 were high reaching an average value of ca. 22 Euro/t, prices dropped considerably in the year 2006 and continued to fall to values close to zero in 2007 (European Energy Exchange [EEX], 2007g). If it is taken into account that the entire time period is part of the same commitment period it is questionable whether the market provided a correct price signal in the year 2005. Another aspect which has to be considered is the fact that the first trading period 2005-2007 is characterized by generous allocation plans with unambitious reduction targets. So if the markets failed to provide an adequate price signal the central question is: What is an adequate price for CO_2 emissions saved by renewable electricity generation and how can its price effect be determined?

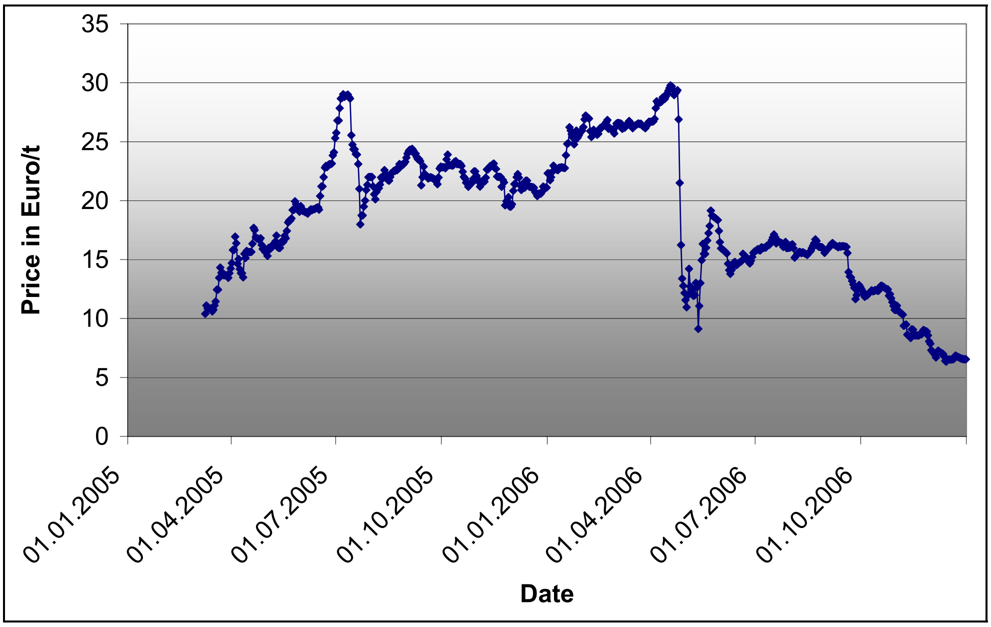

Figure 6-12: Development of EUA prices

Source: Data based on European Energy Exchange [EEX], 2007a

In the given situation the development of a simulation that reproduces market results on the CO_2 markets doesn't seem to be adequate. The alternative approach selected for this study is to determine the cost of alternative options producing the same amount of CO_2 savings as the German supported renewable electricity generation.

6.1.3.1 Estimations of the volume and value of the CO_2 savings created by the supported renewable electricity generation

In order to determine the impact of renewable electricity generation on the CO_2 emission in the German electricity sector the calibrated model is used to simulate the electricity market for the years 2004, 2005, and 2006. Similar to the analysis of market prices in Chapter 6.1.2 50 simulations are carried out for each year. The model calculates the CO_2 emissions of each running power plant according to Formula 6-3:

Formula 6-3: Calculation of the annual CO_2 emissions in PowerACE

$$\alpha = \sum_h \sum_i \frac{v_{i,h} \cdot e_f}{\eta_i};$$

Legend:

Variables			**Unit**	**Indices**		
e	=	CO_2-emission factor	[t CO_2/MWh]	f	=	Fuel
v	=	Hourly electricity generation of plant	[MWh]	h	=	Hour
α	=	Annual CO_2 emissions	[t]	i	=	Plant
η	=	Efficiency	[%]			

The resulting time series is calculated as average of the simulation runs in order to level out variations caused by the random variables used to simulate power plant outages. In a second step the same procedure is applied to 50 simulation runs without renewable electricity production supported by the feed-in tariff. Since the development of large hydro plants has not yet been affected by the renewable support scheme, electricity production of large hydro plants is taken into account in both simulation settings. The resulting CO_2 emissions are compared for both time series. An overview of the simulation results is given in Figure 6-13.

Since PowerACE does not account for the additional CO_2 emissions caused by partial load operation of conventional power plants due to renewable electricity generation an adjustment of the results is necessary. Based on an existing review of different approaches to the calculation of CO_2 savings (Klobasa and Ragwitz, 2005a), a reduction factor of 10 % is assumed which is the highest value of the compared studies. The results of the corrected CO_2 savings are presented in Table 6-10.

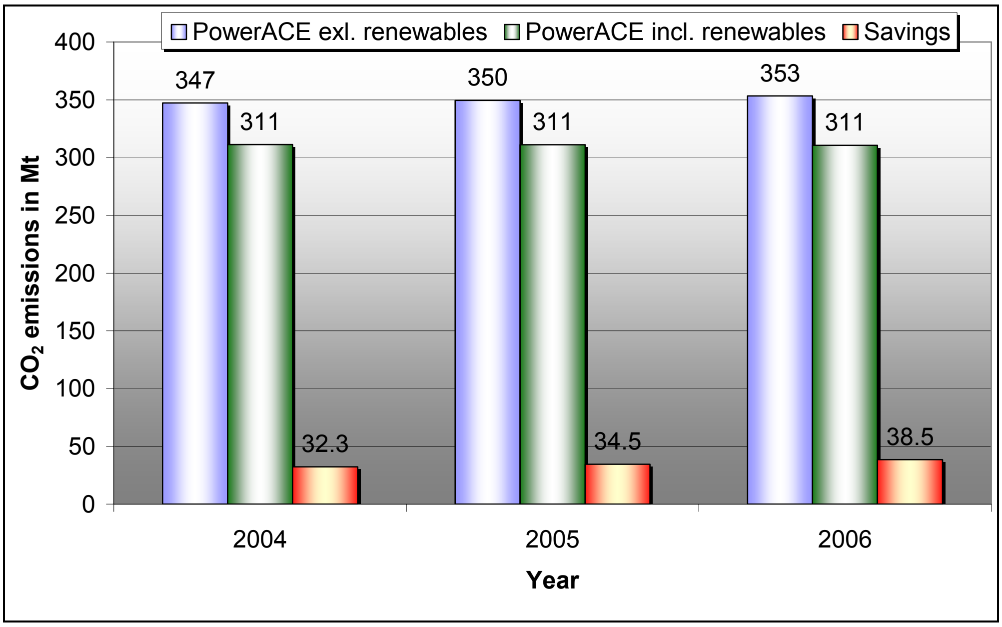

Figure 6-13: Simulated annual CO_2 emissions of the German electricity sector
Source: own illustration

Table 6-10: Corrected CO_2 savings by renewable electricity generation

Category	Year	Excl. EEG Mt	Incl. EEG Mt	Difference Mt	Partial load reduction %	Corrected savings Mt	Renewable Generation TWh	Specific savings kg/MWh
CO_2 emissions	2004	347.2	311.3	35.9	10	**32.3**	41.5	778
CO_2 emissions	2005	349.5	311.2	38.3	10	**34.5**	45.5	758
CO_2 emissions	2006	353.4	310.6	42.8	10	**38.5**	52.2	738

Although PowerACE allows for the calculation of CO_2 savings on a very high detail level, it seems to be important to compare the results of the calculated CO_2 savings with the literature in order to evaluate the results. Klobasa and Ragwitz (Klobasa and Ragwitz, 2005a) provide an overview of existing studies and provide an own estimation of the CO_2 savings in the year

2003. An overview of some studies presented in the review by Klobasa and Ragwitz is given in Table 6-11. The results show that the calculated CO_2 savings are higher in the selected literature. Thereby it has to be taken into account that all the studies deal with the period before the introduction of the European emission trading system which has changed the merit-order curve of power plants. An additional aspect is the higher renewable electricity generation in the year 2005 and 2006 which can lead to the replacement of less CO_2 intensive plants. Based on this comparison it can be stated that the CO_2 savings calculated within this thesis represent a conservative calculation of the CO_2 savings by renewable electricity generation.

Table 6-11: Selected studies on CO_2 savings of renewable electricity generation

	Klobasa and Ragwitz (2005)	**Klobasa and Ragwitz (2005)**	**Sontow, 2000**	**Geiger et al., 2004**
Year	2003	2003	Before 2000	Plant portolio 2000,
Technology	Renewables incl. large hydro	Savings excl. hydro	Wind	Wind (15 GW)
Savings	943 kg/MWh	875 kg/MWh	800 kg/MWh	828 kg/MWh

Source: All values are taken from the overview given in Klobasa and Ragwitz, 2005a

The value of the created CO_2 savings in the year 2006 on the CO_2 market can be calculated by multiplying the savings with the average market price of 17 Euro/t of the emission trading at the European Energy Echange (European Energy Exchange [EEX], 2007b). The resulting value reaches ca. 655 million Euro. Without the supported electricity generation it is likely that generation companies would have to purchase emission allowances of the given value if the same emission target has to be reached. Due to the very volatile development of market prices in the first trading period the calculated value is subject to considerable uncertainty. Average market prices in the year 2007 reach values close to zero while future prices for the second trading period reach prices above 23 Euro/t (European Energy Exchange [EEX], 2007g).

6.1.3.2 Options for the creation of additional CO_2 savings

6.1.3.2.1 Plant dispatch

One option to save CO_2 emissions in the electricity sector is plant dispatch. The utilization of less CO_2 intensive plants such as gas fired plants can be increased at the cost of CO_2 intensive plants. If the price of CO_2 emissions is included into the calculation of variable cost, higher prices should lead to a higher utilization of less CO_2 intensive plants. This effect can only take place if the most CO_2 intensive power plants such as lignite power plants integrate most of the CO_2 price into the calculation of their electricity prices. The very low integration of CO_2 prices of lignite power plants determined in the calibration procedure for the year 2006 reduces the sensitivity of plant dispatch to CO_2 prices heavily. However, in order to assess the maximum possible savings at given CO_2 prices the integration of CO_2 prices into the calculation of the bid prices is set to 100 % for all plants. In a next step the PowerACE Cluster System is run without renewable electricity generation for the year 2006. Beginning with the average CO_2 price of 17 Euro/t in the year 2006, the CO_2 price is increased in steps of 1 Euro/t to 97 Euro/t. For each price step the simulation is run 50 times and the average CO_2 emissions are determined. Due to the number of required simulation runs this case study leads to even higher requirements on the computational resources than the case study carried out in Chapter 6.1.2. The results are presented in Figure 6-14.

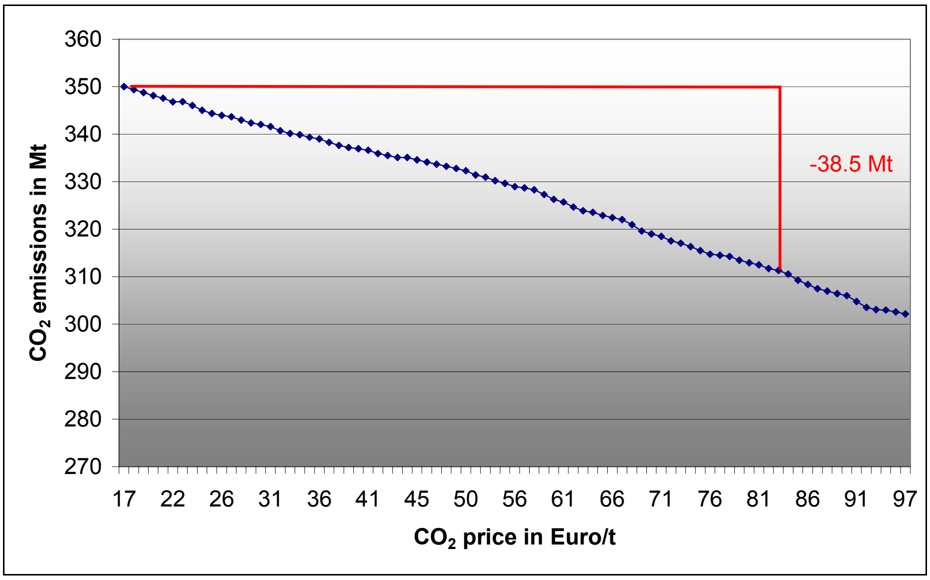

Figure 6-14: Simulated CO_2 emissions in the German electricity sector
Source: own illustration

The results show that even with the full integration of CO_2 prices into the cost calculation of power plants CO_2 prices need to increase to 83 Euro/t in order to reduce the CO_2 emissions by 38.5 Mt by plant dispatch only.

6.1.3.2.2 Replacement of power plants

Another option to reduce CO_2 emissions in the electricity sector is the replacement of old power plants with high CO_2 emissions. However, alternative savings for the CO_2 savings created by renewable electricity generation could only be reached by the replacement of plants before the economic lifetime. If power plants are replaced before the end of their economic lifetime, capital costs have to be taken into account. As a consequence it is likely that generation companies only replace their existing plants if the full cost of the new plant is below the variable generation cost of the old plant. In order to calculate the annuity of the capital cost, an interest rate of 10 % is applied which can be considered to be at the very low end of interest rates that are applied by private investors who normally require interest rates of more than 10 % (Nyboer, 1997). The most important parameters for investments in new plants are given in Table 6-12.

Table 6-12: Data on investments in new plants

Fuel	Efficiency %	Investment €/kW	Interest rate %	Depreciation Years	Utilization Hours per year
Hard coal (HC)	45	1,174	10	25	8,000
Lignite (LG)	44	1,350	10	25	8,000
Gas (CC)	58	470	10	20	6,000

Formula 6-4: Calculation of the generation cost of a new plant

$$\chi = \frac{k}{u_i} \cdot \frac{\delta}{1-(1+\delta)^{-\psi}} + \frac{p_f}{\eta_i} + o + \frac{z}{\eta_i} \cdot e_f$$

Legend:

Variables			Unit	Indices
e	=	CO_2 –emission factor	[t CO_2/MWh]	f = Fuel
k	=	Investment	[Euro]	i = Index of plant
o	=	Variable operation and maintenance cost	[Euro/MWh]	
p	=	Fuel price	[Euro/MWh]	
u	=	Utilization	[Hours]	
z	=	CO_2 price	[Euro/t]	
δ	=	Interest rate	[%]	
η	=	Efficiency of plant	[%]	
χ	=	Generation cost of new plant	[Euro/MWh]	
ψ	=	Lifetime of plant	[Years]	

Formula 6-5: Calculation of the CO_2 savings of the replacement of an old plant

$$\kappa = \left(\frac{e_f \cdot g_j \cdot u_j}{\eta_j} \right) - \left(\frac{e_f \cdot g_i \cdot u_i}{\eta_i} \right)$$

Legend:

Variables			Unit	Indices
e	=	CO_2-emission factor	[Kg/MWh]	f = Fuel
η	=	Efficiency of plant	[%]	i = Index of plant
g	=	Capacity of plant	[Years]	j = Index old plant
κ	=	CO_2 savings of new plant	[Kg]	
u	=	Utilization of plant	[Euro/MWh]	

Another issue is the calculation of the CO_2 savings caused by the replacement of an old plant. For this analysis the PowerACE Cluster System is used. Selected plants are replaced by new plants in the data set and the simulation is run with the CO_2 price necessary to trigger the investment. As a result the CO_2 savings are calculated. These savings represent a combination of changed plant dispatch and the effect of the replacement of old power plants. Without the support of the model the results of the effect of a new power plant would have to be calculated manually according to the following formula.

It has to be taken into account that new plants are characterized by lower variable cost. This leads to the fact that a new plant also has a lower position in the merit-order curve. As a result the utilization of other probably more CO_2 intensive plants is reduced. This aspect is taken into account in the PowerACE simulation but is very difficult to integrate in the manual calculation. In order to estimate the necessary CO_2 price for the creation of additional savings an existing plant is compared to a new plant. The CO_2 price is adjusted until the generation cost of the new plant according to Formula 6-4 is below the variable generation cost of the old plant. In order to assess the potential savings by the replacement of older plants, two different scenarios are analysed. The first scenario allows no changes within the share of the different fuels, which means that lignite power plants can only be replaced by new lignite power plants. The rationale behind this restriction is that it may not be possible to have a heavy change in the fuel mix due to the existing infrastructure such as plant location, mining and transport capacities. A cheap option can be the replacement of old gas fired plants, but the possible savings are very low. Considerable savings can be achieved by the replacement of the least efficient hard coal and lignite power plants. But in order to create savings of the same size as those of the supported renewable electricity generation a CO_2 price of 53 Euro/t has to be applied for the year 2006. All in all a capacity of ca. 5.7 GW lignite fired plants and of ca. 7.2 GW hard coal fired plants must be replaced before the end of their lifetime in order to create the required CO_2 savings. An overview of the results of the scenario where no fuel switch is allowed is given in Figure 6-15.

Based on the applied rationale, cheaper CO_2 savings can be created by the replacement of old hard coal and lignite fired plants with gas fired combined cycle power plants. In order to reach the required savings a CO_2 price of 37 Euro/t is necessary. In total ca 6.2 GW of hard coal and 0.3 GW of lignite fired plants need to be replaced by gas fired combined cycle power plants leading to an additional gas demand. Since the additional gas demand of the power sector would increase the German energy demand, it is questionable whether this development could take place without increasing gas prices and extensions of the transport infrastructure for natural gas. An overview of the results of the scenario where fuel switch is allowed is given in Figure 6-16.

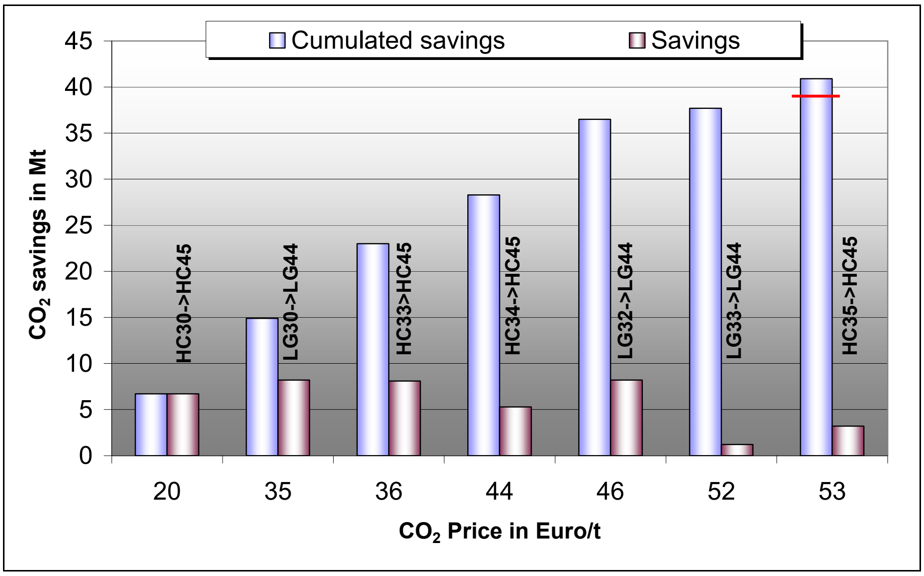

Figure 6-15: CO_2 savings by the replacement of older plants (same fuel share scenario)

Legend: Abbreviations XX00; XX = Technology; 00 = Efficiency; HC = Hard coal, LG = Lignite, CC = Gas Combined Cycle power plant

Source: own illustration

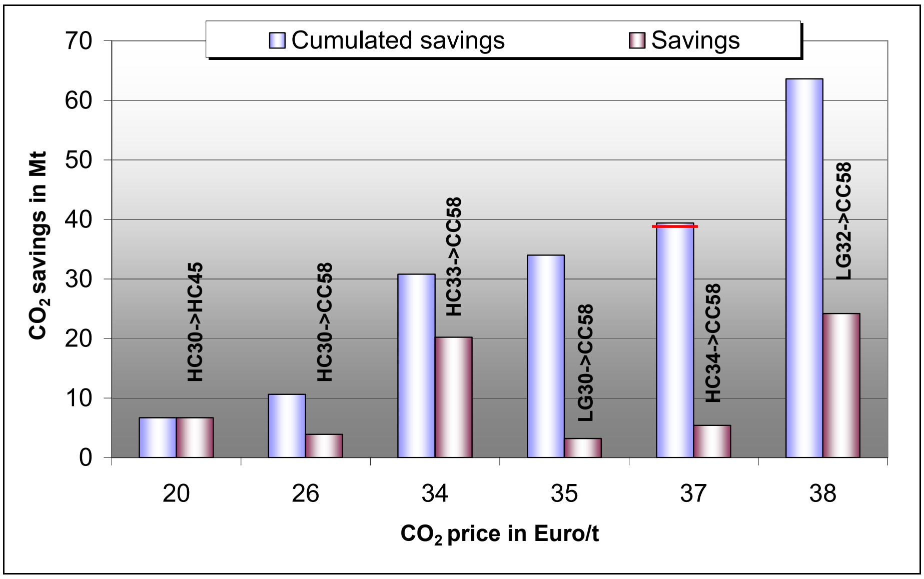

Figure 6-16: CO_2 savings by the replacement of older plants (gas scenario)

Legend: Abbreviations XX00; XX = Technology; 00 = Efficiency; HC = Hard coal, LG = Lignite, CC = Gas Combined Cycle power plant

Source: own illustration

In order to analyse the sensitivity of the resulting CO_2 price towards the underlying assumptions for the calculation of the cost of investment decisions, a sensitivity analysis is carried out by a variation of the most important parameters. As example the replacement of a hard coal fired plant of an efficiency of 30 % by a new hard coal fired plant with an efficiency of 45 % is selected. The results are presented in Table 6-13. It can be seen that the results are very sensitive to all underlying parameters. This has to be taken into account for the evaluation of the results.

Table 6-13: Sensitivity analysis for the parameters of the investment decision

Category	**Unit**	**Variable**			**Resulting CO_2 price**		
		Low	**Reference**	**High**	**Low €/t**	**Reference €/t**	**High €/t**
Time period	Years	20	25	30	23	20	18
Interest rate	%	8	10	12	14	20	29
Fuel price	€/MWh	6	7.98	10	26	20	16
Efficiency of new plant	%	44	45	46	22	20	18
Utilisation of new plant	Full load hours	7,500	8,000	8,500	23	20	17

6.1.3.2.3 Savings within the industry sector

The analysis carried out in the previous sections shows that the replacement of the CO_2 savings that are created by renewable electricity generation within the electricity sector can only be reached with a heavy increase of CO_2 prices. Another source for CO_2 savings within Germany could be the industry sector. The industry sector is also part of the European Emission Trading System. A central problem for the assessment of the saving potential is the complexity of the sector. In order to provide an estimation of the amount of the additional savings that can be created in the industry sector the ISI-Industry model developed at the Fraunhofer Institute for Systems and Innovation Research is utilized. The model is based on a detailed technology database containing detailed techno economic data on measures to save energy and CO_2 in the industry sector. Based on assumptions of the economic development and the autonomous penetration of saving measures the additional saving potential and the corresponding cost are calculated. A more detailed description of the model can be found in Fleiter 2007 (Fleiter, 2007). Calculations with this model and the fuel prices of the year 2006 show that additional annual CO_2 savings of 1.9 Mt can be created at the cost of 20 Euro/t in Germany. At the price of 58 Euro/t total savings of 2.1 Mt can be created. These figures show that the saving potential in the German industry sector is substantial but far below the 38.6 Mt CO_2 saved by the supported renewable electricity generation.

6.1.3.2.4 Aggregated supply curve for Germany and Europe

If all analysed CO_2 saving options in Germany are aggregated, a supply curve for additional CO_2 savings can be created. The resulting aggregated supply curve shows that a CO_2 price of 37 Euro/t would be required to keep CO_2 emissions on the current level without the supported renewable electricity generation. The figure shows that the position of the saving target is reached within the supply step at 37 Euro/t.

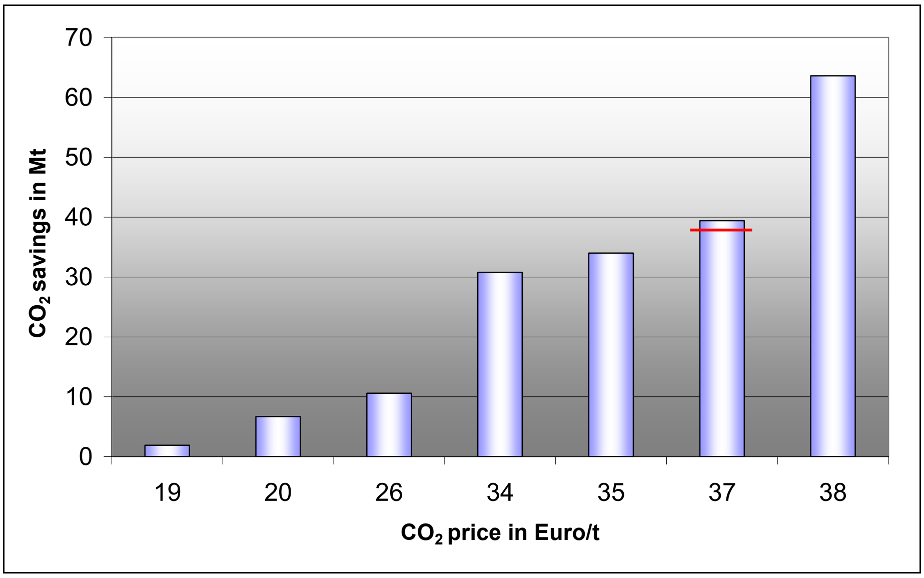

Figure 6-17: Aggregated supply curve of alternative CO_2 saving options in Germany
Source: own illustration

In addition to CO_2 savings created within a country it is also possible within the European Union Trading system to take credit for savings on international level. One option could be the use of flexible mechanisms such as the clean development mechanism which can create emission allowances to be accounted for in the European Emission Trading scheme. In order to assess the potential contribution of flexible mechanisms it is necessary to determine the available amount of additional emission allowances and the corresponding price. Both values are difficult to assess. One possible guideline concerning the volume could be derived from the allocation rules of the European Union for the trading period 2008-2012 which allows the countries to use a maximum of 50 % (Schleich et al., 2007, p.5) of emission allowances created by flexible mechanisms for the achievement of their emission budget. If this rule is applied to the CO_2 savings created by renewable energy sources, the maximum volume of certificates achieved by flexible mechanisms can be set to 19.25 Mt in the year 2006. The next issue is the price of these additional certificates. The available market data state that the prices for these certificates [CER] were within the range of 3.15 Euro/t to 20 Euro/t (PointCarbon, 2007, p.23). It is likely that additional certificates would achieve prices at the upper end of this price span. Nevertheless it is assumed that 19.25 Mt of CER could be created at the average CO_2 price of 17 Euro/t in 2006, which would have no impact on CO_2 prices thus representing a very conservative estimation. Another source for additional savings could be the purchase of certificates created by savings within the industry sector and the electricity sector of countries taking part in the European Emission Trading System. Again the available data is scarce. The ISI industry model can be used to provide an estimation of the potential savings within the Industry sector of the European Union [EU 25]. According to the model 6.4 Mt can be provided at the price of 19 Euro/t. At the price of 32 Euro/t total CO_2 savings of ca. 7 Mt can be provided. A detailed analysis of the possible savings that can be created by the replacement of older power plants in the entire European Union is beyond the scope of this thesis. However, an estimation of the maximum saving potential at a given price level can be provided by comparing the thermal electricity generation in Europe to the German situation. According to the available data Germany accounts for ca. 22 % of the European thermal power generation in Europe (Eurostat, 2007, p.2; Bundesministerium für Wirtschaft und Technologie [BMWI], 2007a). By upscaling the aggregated CO_2 saving curve for the replacement of power plants with factor 4.6, a very rough approximation of the European saving potential can be achieved. Considering the fact that Germany accounts for ten of the 30 most CO_2 intensive power plants in Europe (WWF, 2007), it may be safely stated that this approximation provides an overestimation of the potential savings. Thereby it has to be stated that the large scale replacement of fossil fired plants by nuclear power plants is excluded from the analysis since it is unlikely from the current political perspective. Based on these assumptions an aggregated supply curve for additional savings on European level can be developed. The resulting aggregate supply curve presented in Figure 6-18 shows that a CO_2 price of ca 20 Euro/t would be necessary to create the required CO_2 savings. For the evaluation of the results it has to be taken into account that the gas price of the year 2006 is very high which makes any fuel switch from CO_2 intensive lignite or coal firing to gas is more expensive than in previous years.

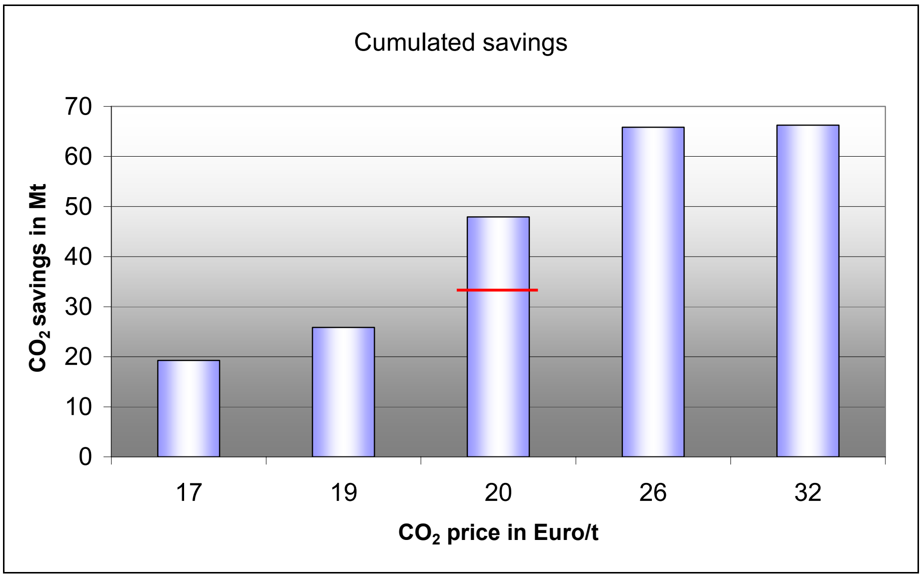

Figure 6-18: Aggregated supply curve of alternative CO_2 saving options in Europe
Source: own illustration

6.1.3.3 Volume of the CO_2 price effect

After the estimation of the likely CO_2 price of the year 2006 without the supported renewable electricity generation the volume of the CO_2 price effect on the electricity sector can be determined. Similar to the determination of the merit-order effect the volume of the CO_2 price effect is determined with the help of the PowerACE Cluster System. In order to provide a lower end estimation of the volume of the effect the simulation platform is run 50 times without the supported renewable electricity generation and a CO_2 price of 20 Euro/t. In a next step the simulation platform is run 50 times with the supported renewable electricity generation and the actual CO_2 prices of the year 2006. In both cases the average hourly time series of market prices is calculated. The volume of the price effect is calculated according to Formula 6-6. The price difference of both time series is determined for each hour and multiplied by the corresponding load. These values are summed up and the volume of the merit-order effect (see Figure 6-11) is subtracted in order to isolate the CO_2 price effect. An overview of the results is given in Table 6-14. Based on the described calculations, the CO_2 price effect can be estimated to an average price reduction of 2.49 Euro/MWh. The total volume of the CO_2 price effect reaches 1.38 billion Euro in Germany. Another result of the analysis is that the CO_2 savings achieved by renewable electricity generation cannot easily be achieved by other measures. The creation of comparable CO_2 savings within the European trading scheme can be costly, especially if the savings need to be created in Germany.

Formula 6-6: Calculation of the CO_2 price effect

$$q = \left(\sum_{h=1}^{h=8760} (x_h - p_h) \cdot d_h\right) - v;$$

Legend:

Variables			Unit	Indices
d	=	Total electricity demand	[MWh]	h = Hour
p	=	Price including renewable generation	[Euro/MWh]	
q	=	Volume CO_2 price effect	[Euro]	
v	=	Total volume of the merit-order effect	[Euro]	
x	=	Price excluding renewable generation	[Euro/MWh]	

Table 6-14: Resulting volume of the CO_2 price effect

	Simulated electricity generation	Average price reduction		Volume		
		Merit-order effect	CO_2 price effect	Both effects	Merit-order effect	CO_2 price effect
Year	TWh	€/MWh	€/MWh	Billion €	Billion €	Billion €
2006	52.2	7.83	2.49	6.36	4.98	1.38

6.1.3.3.1 Sensitivity Analysis

Due to the considerable uncertainty connected with the estimation of the CO_2 price it seems to be necessary to carry out a sensitivity analysis of the calculated CO_2 price effect with regard to the assumed CO_2 price without supported renewable electricity generation. Besides the uncertainty concerning economic parametes like fuel prices an important issue is the availability of cheap emission allowances created by flexible mechanisms. In the case that more than half of the required CO_2 savings could be created this way the CO_2 price effect could drop. In case that all required savings could be covered this way the CO_2 price effect could drop to zero. In order to account for these uncertainties the 50 simulation runs with CO_2 prices between 17 Euro/t and 29 Euro/t are carried out with the PowerACE Cluster System and the corresponding volume of the CO_2 price is calculated. The results presented in Table 6-15 show that the volume of the CO_2 price effect is very sensitive to the assumed CO_2 price. A reduction of the CO_2 price of 1 Euro/t leads to a reduction of the volume of the CO_2 price effect of 31 %. An increase of the CO_2 price to 29 Euro/t increases the CO_2 price effect by 278 %. The relative change of the CO_2 price effect changes almost in line with a relative change of the increase in CO_2 prices. Due to the high sensitivity of the results it has to be stated that the presented results on the CO_2 price effect are connected with considerable uncertainty. Nevertheless the considerable size indicates its importance.

Table 6-15: Sensitivity analysis of the CO_2 price effect

CO_2 price without supported renewable electricity generation	**Increase of the CO_2 price**	**Volume**			**Relative change**
		Both effects	**Merit-order effect**	**CO_2 price effect**	
€/t	€/t	Billion €	Billion €	Billion €	%
17	0	4.98	4.98	0	-100
19	2	5.93	4.98	0.95	-31
20	3	6.36	4.98	1.38	0
22	5	7.21	4.98	2.23	62
25	8	8.47	4.98	3.49	153
29	12	10.19	4.98	5.21	278

6.2 Balancing and management of the electricity system

6.2.1 Additional cost for reserve capacity and energy

Another aspect to be taken into account for the analysis of the impact of renewable electricity generation on the electricity sector is the impact on the reserve capacities necessary for the balancing of the system. Reserve capacities are necessary to keep the system in balance in case of unforeseen developments of electricity demand or outages of power plants. As described in Chapter 2, there are three kinds of reserve capacities: The primary reserve, the secondary reserve and the minute reserve. The necessity of additional reserve capacity is discussed because of the fluctuating character of renewable electricity generation, especially wind generation. Reserve capacities may be required if the actual electricity generation by wind energy deviates from the intra-day projection of electricity generation by wind energy. Additional reserve capacities can lead to additional cost to be integrated into the grid fees which have to be paid by the consumers in the end. A recent study on the integration of wind energy into the German electricity grid also analyses the requirements for additional reserve capacities (Deutsche Energie-Agentur [DENA], 2005). The study states that no additional reserve capacities are needed for the primary and the secondary reserve (Deutsche Energie-Agentur [DENA], 2005). This statement can be supported by an analysis of the contracted reserve capacities in Germany (see Figure 6-19).

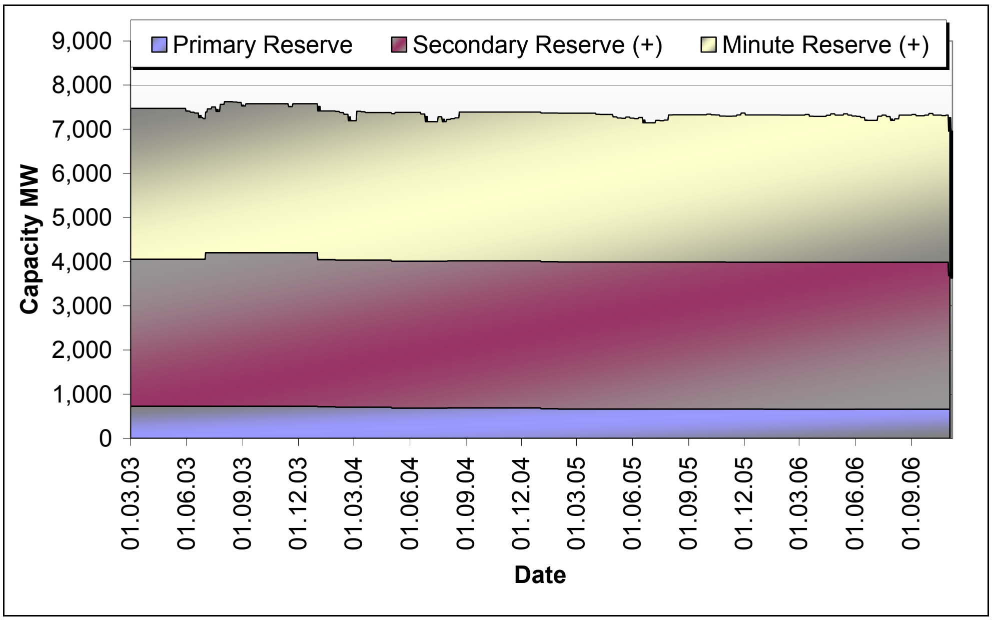

Figure 6-19: Contracted positive reserve capacities in Germany

Sources: based on Verband der Industriellen Energie- und Kraftwerkswirtschaft [VIK], 2004; Verband der Industriellen Energie- und Kraftwerkswirtschaft [VIK], 2005; Verband der Industriellen Energie- und Kraftwerkswirtschaft [VIK], 2006; RWE Transportnetz Strom et al., 2007; Verband der Industriellen Energie- und Kraftwerkswirtschaft [VIK], 2007

In case of primary reserve the development shows a slight reduction of the contracted reserve throughout the past years. The same seems to be true for the secondary reserve where no major increases can be discovered in the available data set. In the given study it is stated that the fluctuations of wind energy mainly affect the demand for minute reserve and a new reserve which is called hourly reserve. The studies calculated an additional average reserve demand of 8.1 % (Deutsche Energie-Agentur [DENA], 2005, p.254) for the year 2003. If these figures are transferred to the year 2006, an additional positive reserve demand of 1670 MW can be estimated. In case of negative reserve an average value of 5 % of the installed capacity is given for the year 2003. If this value is transferred to the installed capacity of 2006, a required average minute reserve of 1030 MW can be estimated. However, it has to be stated that the given study uses a very conservative assumption on the quality of the German prognosis of wind energy. The study assumes a standard deviation of the prognosis of 4.92 % for the year 2003 (Deutsche Energie-Agentur [DENA], 2005, p.254).The quality of the four hour ahead prognosis in terms of the standard deviation has already reached a value of 3.8 % (Energy & Meteo Systems GmbH, 2007), respectively 3.6 % in 2004/2005 (Biermann et al., 2005). In the given case study this quality has been assumed to be not available before 2015. A more recent estimation of the requirements of additional reserve capacity is presented by Klobasa and Obersteiner (Klobasa and Obersteiner, 2006). The authors use a simulation approach for the assessment of the required reserve. On condition of a prognosis error of 4.5 % and a different approach the maximum additional reserve demand of ca. 4 % of the installed capacity or 825 MW can be derived from the presented results.

Table 6-16: Estimation of the cost of reserve capacity for wind energy

Category	**Unit**	**Estimation based on Dena (2005)**	**Estimation based on Klobasa and Obersteiner (2006)**
Prognosis Error [RMSE]	% of installed capacity	4.92	4.50
Installed Capacity	MW	20622	20622
Required positive reserve	MW	1670	825
Required negative reserve	MW	1030	825
Daily capacity price (positive)	€/MW	152	152
Daily capacity price (negative)	€/MW	98	98
Capacity cost	Million €	**129**	**75**

Source: Data on capacity prices Verband der Industriellen Energie- und Kraftwerkswirtschaft [VIK], 2007)

The actual cost of the required additional reserve can be estimated by multiplying the required capacity by the corresponding average capacity price of minute reserve in the year 2006 (Verband der Industriellen Energie- und Kraftwerkswirtschaft [VIK], 2007). Based on this calculation the annual cost of required reserve can be estimated to 75 million Euro for the year 2006. Based on the data provided by Dena, the costs reach 129 million Euro. Since the quality of the available prognoses on wind energy with prognosis errors of less than 4 % (Energy & Meteo Systems GmbH, 2007, Biermann et al., 2005) has already improved beyond the assumptions of both studies, these results should be considered as a high estimate of the actual cost. In addition it has to be taken into account that the reserve capacity bought by the German grid operators did not increase throughout the past years. This could be an indicator that the reserve capacity required for the balancing of wind energy can be covered by overcapacities within the existing reserves.

Besides the payments for the reserve capacity additional payments in terms of a work price are necessary if this reserve capacity is utilized as reserve energy. In the literature an estimation can be found which states an additional demand for minute reserve energy of ca. 2.1 TWh positive and 1.4 TWh negative minute reserve for a wind portfolio producing ca. 36.8 TWh of wind energy (Deutsche Energie-Agentur [DENA], 2005, p. 270 ff.). If these values are adjusted to the actual electricity generation of wind energy in the year 2006, the reserve energy demand for the year 2006 reaches 1.8 TWh of positive minute reserve and 1.2 TWh of negative reserve demand. In order to validate these values the existing demand for minute reserve energy has to be analysed. A complete time series of the minute reserve energy demand is available for the transmission zones of RWE, Vattenfall and EnBW. No data is available for the Eon transmission zone. If the available values are scaled according to the overall demand for minute reserve, the total demand for minute reserve energy can be estimated to ca. 160 GWh of positive reserve energy and 150 GWh of negative reserve energy. Although these figures have to be considered as an estimate due to the lack of exact data on the Eon transmission zone, it is obvious that additional demand for minute reserve energy presented in the given study is not in line with the real world situation. There are two possible reasons. The first reason could be that the estimated demand for additional minute reserve is far too high. Another reason could be that a part of the estimated minute reserve demand is covered by secondary reserve energy. In order to provide an upper estimation of the cost it is assumed that the remaining demand for reserve energy is covered by secondary reserve. The next step is to determine the actual cost of the reserve energy demand. In case of minute reserve and secondary reserve minimum and maximum work prices are published (Verband der Industriellen Energie- und Kraftwerkswirtschaft [VIK], 2007). Due to the low utilization of the minute reserve it can be assumed that the actual average price is very close to the published minimum price. In case of the secondary reserve the average work price is calculated as the average of the minimum and maximum work price. Based on these assumptions, the cost of the additional reserve energy demand caused by wind energy can be estimated to 177 million Euro. Since this estimation is based on the assumption that the entire deviation between the overall minute reserve demand and the published additional minute reserve demand (Deutsche Energie-Agentur [DENA], 2005) is caused by additional utilization of the secondary reserve, this number should be considered as a very high estimate of the cost. If the calculated cost of the additional reserve capacity and reserve energy demand are added up, the total cost for the balancing of the system can be estimated to a maximum of 252 million Euro. The assessment of the result as a high estimate is backed by the fact that a model based approach which can be found in the literature states cost which are more than three times lower than the presented results (Klobasa and Obersteiner, 2006, p. 897). Thereby it has to be stated that the given approach uses a model based cost orientated approach and not on the higher market prices for reserve energy.

Table 6-17: Calculation of the cost of additional reserve demand caused by wind energy

Category	**Utilized reserve energy** GWh	**Work price** €/MWh	**Cost** Million €
Category minute reserve		**Minute reserve**	
Positive reserve energy	160	134	21.4
Negative reserve energy	150	2	0.3
Category secondary reserve		**Secondary reserve**	
Positive reserve energy	1,640	92.2	151.2
Negative reserve energy	750	5.6	4.2
		Total	**177**

6.2.2 Creation of the monthly base load block

The electricity generation by renewable energy sources has to be bought by the grid operators. The electricity is passed on to the suppliers as a base load block. According to current practice the volume of this base load block is determined by the German association of grid operators [VDN] at the tenth day of the preceding month. If the projected volume does not meet the actual generation, the differences are integrated into the calculation of the base load block for the remaining months at the tenth of the next month.

The crucial issue for the creation of the base load block is that electricity generation by renewable energy sources has a fluctuating character. In order to create a base load block the grid operators have to trade with the renewable electricity generation. The central basis is a day-ahead projection of renewable electricity generation. Based on this projection grid operators have to buy or sell electricity in order to create a base load block. An overview of the balancing trades is given in Figure 6-20.

A central question is whether these balancing trades lead to additional cost for the grid operators which have to be integrated into the grid fees. In order to analyse this aspect it seems to be necessary to determine the volume of balancing trades. This analysis requires an hourly load profile of renewable electricity generation and the corresponding base load blocks for an entire year. The hourly load profile of renewable electricity generation is part of the PowerACE model (see also Chapter 5). The volume of the base load blocks of the year 2006 is also available (Verband der Netzbetreiber [VDN], 2007c).

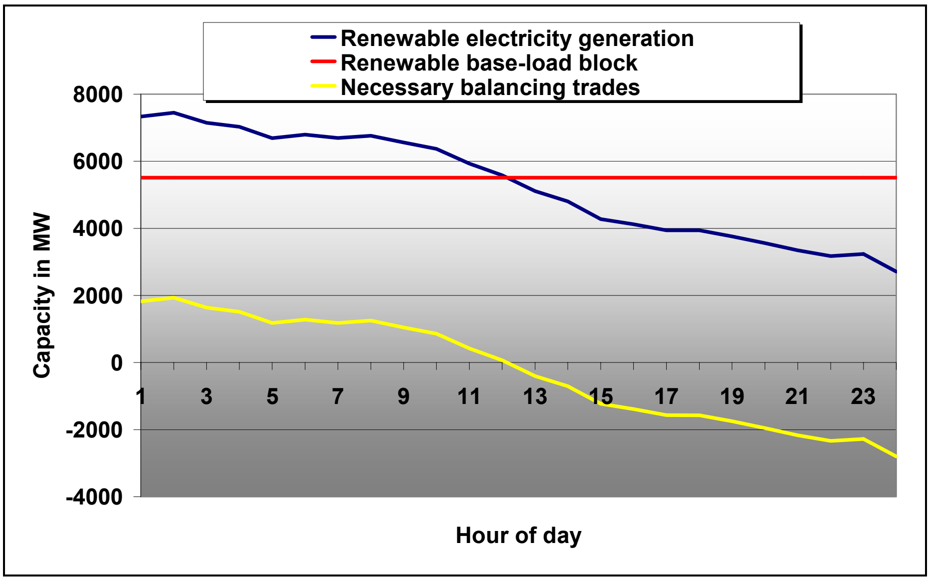

Figure 6-20: Balancing trades on a selected day
Source: own illustration

Formula 6-7: Calculation of the cost of the creation of the renewable base load block

$$c = \sum_{h=1}^{h=n} \left((r_h - \tau_h) \cdot p_h \right)$$

Legend:

Variables			**Unit**	**Indices**
c	=	Annual cost of the day-ahead prognosis deviation	[Euro]	h = Hour
r	=	Electricity generation of wind energy	[MWh]	
n	=	Length of the time series in hours	[Hour]	
p	=	Average price on the day-ahead market	[Euro/MWh]	
τ	=	Base load block of renewable electricity generation	[MWh]	

A characteristic of the published data on the projected base load blocks is that it leads to an underestimation of renewable electricity generation of 5.5 TWh. If the cost of the day-ahead creation of the base load block is calculated according to Formula 6-7, the underestimation of the renewable electricity generation leads to a considerable profit which may not occur in reality as the underestimated volume has to be integrated into a delivery of a base-load block of the next year. In order to eliminate this bias, the average market price of a base load block of 50.6 Euro/MWh (see European Energy Exchange [EEX], 2007e) is multiplied by the volume of the underestimated electricity generation and subtracted from the results of the calculation according to Formula 6-7. Based on these assumptions the value of the underestimated renewable electricity generation in the year 2006 can be estimated to 277 million Euro. If this result is subtracted from the results of the application of Formula 6-7 on the data for the year 2006, a profit of 95 million Euro of the balancing trades is achieved. These figures indicate that the day-ahead balancing trades for the creation of a monthly base load block do not necessarily lead to additional cost. In the analysed year 2006 an additional profit can be generated. But it has to be taken into account that the actual volume of the profit or cost connected with this service heavily depends on the development of market prices and the actual deviation of the day-ahead prognosis of renewable electricity generation from the monthly profile. Therefore it is assumed that the creation of the monthly profile does not lead to additional cost.

6.2.3 Cost of the intra-day profile service

Another aspect of the profile services to be carried out by the grid operators is the intra-day profile service. As described in the previous section the grid operators ensure the delivery of a monthly base load block by day-ahead trades which are based on a day-ahead projection of wind energy. However, due to changing weather conditions the electricity generation by wind energy can deviate from the prognosis on the actual day of delivery. Based on a new intra-day prognosis the grid operators trade on the intra-day markets in order to balance the renewable portfolio. One example of an intra-day market is the intra-day market of the European Energy Exchange [EEX]. The market was introduced in September 2006 (European Energy Exchange [EEX], 2007c) and allows for trades of electricity up to 75 minutes before the actual physical delivery. Other trading opportunities for the grid operators are over the counter [OTC] trades with generation companies. Unfortunately the prices of these OTC contracts are not available for the public. The goal of this section is to provide an estimation of the actual cost that is connected to the intra-day management of the renewable portfolio. The first step of the given task is the analysis of the differences between the day-ahead prognosis and the actual electricity generation. The four German transmission grid operators publish data on the day-ahead prognosis of the hourly wind generation and the actual wind generation within their transmission zone. This data is available for the years 2006 and 2007. In order to analyse the situation on national scale both time series are added up for all four transmission zones. The result is a time series of the deviation of wind generation from the day-ahead prognosis. An overview of the situation in the year 2006 is given in Figure 6-21. It is remarkable to note that the figure shows a bias in the prognosis error. In the given time series the electricity generation by wind energy is systematically overestimated. The sum of all prognosis errors reaches ca. 4 TWh. This structural overestimation leads to higher cost than in case of a balanced prognosis. However, the figure shows that the deviation of actual generation and prognosis is below 2000 MW most of the time. However, there are some hours with extreme deviations of up to 6650 MW. In terms of energy the accumulated intra-day deviation reaches 6.7 TWh or ca. 22 % of the actual generation. These figures indicate that the volume that has to be traded for the intra-day management of the renewable portfolio is considerable. The next step for the analysis of the cost of the intra-day management of the renewable portfolio is to determine the actual value of the trades on the intra- day markets. The central problem is that no data on the over the counter trades is available. The only available indicator for prices on the intra-day market are market prices published by the EEX (European Energy Exchange [EEX], 2007c; European Energy Exchange [EEX], 2007d).

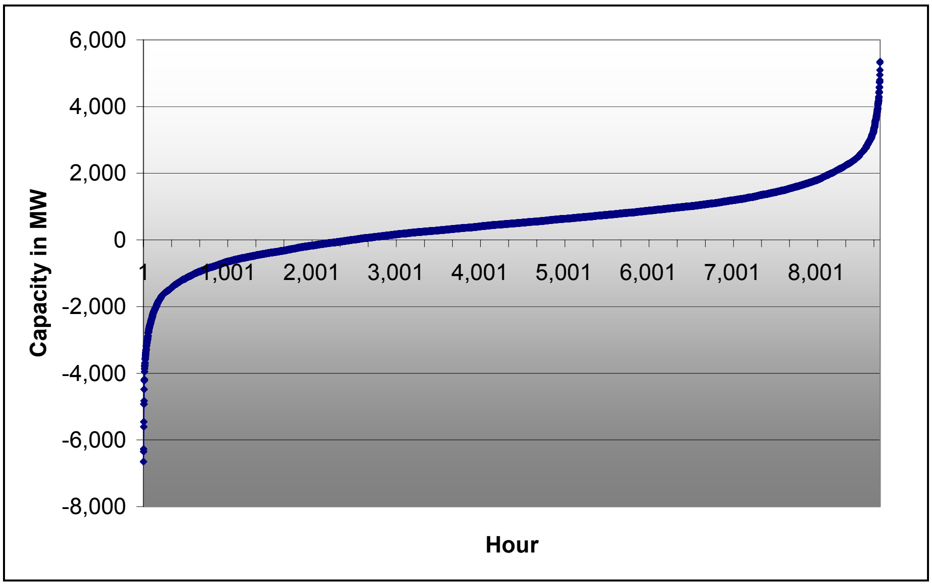

Figure 6-21: Deviation of prognosis and actual wind generation of the year 2006 (sorted)

Sources: based on E.ON Netz, 2007; EnBW Energie Baden-Württemberg AG, 2007a; RWE Transportnetz Strom, 2007; Vattenfall Europe Transmission, 2007b; Vattenfall Europe Transmission, 2007a

As this market started operation in September 2006, there is no hourly time series for an entire year available. The data available for this thesis ranges from September 2006 to the beginning of May 2007. Another aspect which has to be taken into account is the problem that prices are not available for all hours of the period. Especially at the beginning of the time series there are some hours where no clearing price is published which is likely to be caused by the low liquidity of an emerging market. Low liquidity may also lead to extreme prices which may not provide an adequate price signal for the entire electricity sector. But as no other data is available, the analysis has to be based on these prices. The weaknesses described above have to be taken into account in the evaluation of the results. If the available data set is filtered in order to leave out incomplete data, the available time series for the year 2006 is reduced to 1222 hours. By multiplying the deviation by the average market price on the intraday market in the given hour the value of the electricity trades can be calculated. The annual cost can be estimated by an extrapolation to 8760 hours. The formula is given in Formula 6-8. The result of this procedure leads to estimated cost of ca 307 million Euro for the year 2006. If the same procedure is applied to the year 2007, where the available data set amounts to 2049 hours, the estimated annual cost reach 124 million Euro. The considerable difference between both values can be caused by several reasons. One important aspect could be the higher liquidity of the intra-day market in 2007 leading to less volatile market prices. Another aspect could be seasonal differences in the quality of the available wind prognosis as the time series for the year 2006 covers the end of the year while the time series for 2007 covers spring. With regard to these considerations a good approximation of the actual cost could be determined by the average of both values.

Formula 6-8: Estimation of the cost of the intra-day prognosis deviation of wind energy

$$c = \frac{\sum_{h=1}^{h=n}\left(\left(r_h - x_h\right)\cdot p_h\right)}{n}\cdot\iota$$

Legend:

Variables			**Unit**	**Indices**
c	=	Annual cost of the intra-day prognosis deviation	[Euro]	h = Hour
r	=	Electricity generation of wind energy	[MWh]	
ι	=	Number of hours per year (8760)	[None]	
n	=	Length of the time series in hours	[Hour]	
p	=	Average price on the intra-day market	[Euro/MWh]	
x	=	Day-ahead prognosis of el. generation by wind energy	[MWh]	

The average of both values leads to an estimation of the annual cost of 215 million Euro for the cost of the intra-day management of the renewable portfolio. If the bias of the prognosis error is taken into account, the cost could be lower if further improvements of the prognosis of wind energy take place. Considering the incomplete time series of the intra-day market prices, it should be stated that the cost estimation is subject to considerable uncertainty. The cost of this intra-day profile service is integrated into the calculation of the grid fees of the grid operators in the end.

6.2.4 Extension of the electricity grid

Another important aspect in the discussion on renewable electricity generation are the necessary extensions of the electricity grid in order to deal with the increasing renewable electricity generation. The responsibilities for the cost related to the connection of renewable electricity generation to the electricity grid are defined by §13 of the Renewable Energy Act (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2004a). The cost for metering and the connection to the electricity grid have to be paid by the renewable electricity generator. In the end these costs are part of the profit calculation of the renewable investor. As the income of renewable electricity generation is generated by the support scheme, these costs need no further investigation for the analysis of the impact of renewable electricity generation on the electricity sector. Another aspect is the necessary extensions and reinforcements of the electricity grid.

The first step is the analysis of the cost of the necessary grid extensions. Two major studies deal with the analysis of the necessary grid extensions. In Auer et al. (Auer et al., 2004) the available literature on the necessary grid extension on international level is complemented by calculations with the tool GreenNet. The authors derive a cost curve which depends on the share of wind energy in the total electricity consumption. In case of Germany extension costs of 1 Euro/MWh renewable electricity generation can be derived as an upper cost estimate. This value is reached if the entire renewable electricity generation is treated with the same grid extension cost as wind energy, which is likely to be an overestimation of the cost since other technologies such as biomass and hydro power plants reach a higher utilization of their capacity, Another recent study which focuses on Germany only is published by the German Energy Agency [DENA]. The authors derive a cost estimate of 100 Euro/kW per installed kW of wind energy if the installed capacity exceeds 20.000 MW. At the end of 2006 the installed capacity reached 20.622 MW (Deutsches Windenergie Institut [DEWI], 2007). The necessary investments until the end of 2007 are estimated to 275 million Euro. Based on the cost estimate of the study, a necessary investment of 62.2 million Euro can be calculated for the grid integration of wind energy in the year 2006. The comparison shows that the expected grid integration cost are likely to rise. If a technical lifetime of 20 years and an interest rate of 6 % is assumed, the capital cost can be calculated. In a next step this value can be broken down to the total electricity generation of the installed wind capacity for twenty years. The results are specific capital costs for integration into the transmission grid of ca. 0.18 Euro per generated MWh. The annual operation and maintenance costs stated in the given study amount to ca 1.5 % of the investment (Deutsche Energie-Agentur [DENA], 2005, p. 144). If this value is multiplied by 622 MW and divided by the total capacity and an average annual utilization of 1730 full load hours, the additional operation and maintenance costs amount to 0.026 Euro/MWh of renewable electricity generation. In sum the total annual cost of grid extensions necessary for the installed wind capacity of the year 2006 amounts to 6.3 million Euro or 0.18 Euro/MWh_{Wind}.

Formula 6-9: Calculation of the annuity of the grid extension cost

1. Calculation of the annuity of the grid extension cost

$$a = k \cdot \frac{\delta}{1-(1+\delta)^{-\psi}} + o = k \cdot \frac{\delta}{1-(1+\delta)^{-\psi}} + 1.5\% * k$$

2. Calculation of the specific annuity

$$s = \frac{a}{e} = \frac{a}{c \cdot u}$$

Legend:

Variables			Unit	Indices
a	=	Annuity of grid extension cost	[Euro]	
k	=	Investment	[Euro]	
c	=	Installed capacity of wind energy	[MW]	
e	=	Annual electricity production	[MWh]	
o	=	Operation and maintenance cost	[Euro]	
s	=	Specific annuity of the necessary grid extensions	[Euro/MWh]	
u	=	Annual utilization in full load hours (1730)	[Hours]	
δ	=	Interest rate	[%]	
ψ	=	Lifetime	[Years]	

Table 6-18: Results for the calculation of the grid extension cost based on (Deutsche Energie-Agentur [DENA], 2005)

Variable	Value	Unit	Source
Average annual utilization	1,730	h	based on ISET, own calculations
Interest rate	6	%	own assumption
No cost border	20,000	MW	Dena 2005
Installed capacity	20,622	MW	DEWI 2007
Investment grid extensions	100	€/kW	Dena 2005
Operation and maintenace per year	1.5	€/kW	Dena 2005
Investment for 2006	62,200,000	€	own calculations
Annuity	6,355,879	€	own calculations
Specific Annuity inkl. O&M	0.18	€/MWh	own calculations

These values are considerably lower than the cost estimation by Auer et al. However, it has to be taken into account that the cost according to Dena are likely to increase in the next years if the installed capacity of wind energy grows further beyond the value of 20000 MW. For an installed wind capacity of 23000 MW the grid integration cost are likely to reach ca. 0.8[11] Euro/MWh_{Wind}. Another aspect is that the study does not account for the grid extensions on the lower voltage level.

However, this comparison shows that the assumption of 1 Euro per MWh renewable electricity generation can be assumed to be an upper estimation of the cost of the grid extension of the installed renewable capacity of 2006. Based on the supported renewable electricity generation of the year 2006 of 52.2 TWh the very upper end of the cost of the necessary grid extension can be assumed to be ca. 52 million Euro per year.

These figures indicate that the costs of the necessary grid extension reach a volume which is remarkable. But it has to be taken into account that these costs are more than 100 times lower than the overall volume of the support payments. The costs of the necessary grid extensions have to be covered by the grid operators. Finally these costs are integrated into the grid fees which have to be paid by the consumers. An additional aspect which has to be taken into account in this context is that the construction of new power lines can face considerable resistance of the local population. In general the procedures for the authorization of new lines can last several years or even decades.

6.3 The impact of renewable electricity generation on the existing generation companies

Another issue which needs to be discussed for the analysis of the impact of renewable electricity generation on the electricity sector is the impact on the existing generation companies and their facilities.

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11 Own calculations based on (Deutsche Energie-Agentur [DENA], 2005, p.143)

6.3.1 Operation of conventional power plants

An issue which has already been hinted at in the previous section is the fact that the fluctuating renewable electricity generation can increase operation of existing power plants in partial load mode. The operation of power plants in partial load mode (below their net capacity) reduces the efficiency and leads to higher generation cost and CO_2 emissions. This phenomenon occurs mainly due to the fact that the existing power plant portfolio is not optimized for the operation with increasing renewable electricity generation. Estimations of the cost connected with the increased operation in partial load are scarce. One estimation can be found in the literature. The authors state additional cost of 0.4 to 0.9 Euro per MWh electricity generation by wind energy (Auer et al., 2005, p.143). Since the assumed fuel prices in the given study are 40 % below the level of the fuel prices in the year 2006, these figures have to be adjusted. Since fuel prices account for most of the cost connected with the operation in partial load mode, the estimated cost of the given study is multiplied by factor 1.4. This procedure leads to estimated cost of 1.26 Euro/MWh electricity generation by wind energy for the year 2006. If this value is multiplied by the electricity generation by wind energy of the year 2006, the cost of the adjusted operation of the conventional power plant portfolio can be estimated to 38 million Euro.

6.3.2 Lost profits

Another issue which has to be taken into account is the issue of reduced profits for the generation companies. The replacement of the conventional electricity generation by renewable electricity generation and the reduced market prices caused by the merit-order effect discussed in Chapter 6.1.2 should lead to reduced profits in a liberalized electricity market. In the given case profit is defined as market price in a given hour minus variable cost. Additional costs which have to be covered by the generators are the start up costs of power plants, fixed operation and maintenance costs and the capital cost of power plants. In order to assess the impact of renewable electricity generation on the profit of generation companies owning conventional power plants the PowerACE Cluster System is utilized. Again 50 simulation runs with and without supported renewable electricity generation are analysed for the year 2006 with the same settings applied for the analysis of the merit-order effect and the CO_2 price effect. The overall profit is calculated according to Formula 6-10.

Formula 6-10: Calculation of the aggregated profit of generation companies

$$\varepsilon = \sum_i \sum_h (m_h - c_{i,h}) \cdot k_{i,h} = \sum_i \sum_h \left(m_h - \frac{x_{f,h}}{\eta_i} + o_i + \frac{z_f \cdot e_f \cdot \zeta_f}{\eta_i} \cdot \right) \cdot k_{i,h}$$

Legend:

Variables			Unit	Indices		
c	=	Variable generation cost	[Euro/MWh]	f	=	Fuel
e	=	CO_2-emission factor	[t/MWh]	h	=	Hour
k	=	Sold hourly energy of plant	[MWh]	i	=	Index of plant
m	=	Spot market price for electricity	[Euro/MWh]			
o	=	Variable operation and maintenance cost	[Euro/MWh]			
x	=	Fuel price	[Euro/MWh]			
z	=	CO_2 price	[Euro/t]			
ε	=	Profit	[Euro]			
η	=	Efficiency	[%]			
ζ	=	CO_2 price integration factor	[None]			

The results of the calculation show that the overall profit of the generation companies is reduced by ca 5.3 billion Euro. Although this is considerable, it is worthy to note that the volume of the lost profits is ca. 1.1 million Euro lower than the sum of the merit-order effect and the CO_2 price effect of the year 2006. This can be explained by the fact that fuel cost and the opportunity cost for CO_2 are reduced due to the lower CO_2 prices and the lower utilization of power plants.

6.3.3 Impact on investments in the electricity sector

The issue of the impact of renewable electricity generation on investments in the electricity sector deals with a long-term perspective. One aspect which is also part of the current discussion is the aspect of avoided investments in additional conventional power plants. Most of the capacity of hydro power plants, bio fuel fired plants and a small portion of the installed capacity of wind energy can be considered as secure capacity which does not need a back-up of conventional plants. In case of scarce capacity this capacity helps to avoid investments in additional capacity. The crucial issue for the further analysis is the determination of the secure capacity. One model based analysis in the literature states avoided conventional capacity of 1.5 GW for wind energy in the year 2007 (Deutsche Energie-Agentur [DENA], 2005, p.295). In order to determine the possible capacity effect of the entire supported renewable electricity generation the data set of the PowerACE Cluster System is analysed. Basically there are two ways to determine the avoided conventional capacity. The first method is the analysis of the time series of renewable electricity generation by setting an availability requirement, which means that the capacity has to be available at least for a certain percentage of the time of a year. If the availability requirement of 98 % is applied to the simulated renewable electricity generation of the year 2006, a secure capacity of 1840 MW can be calculated. Another method is to determine the reduction of the peak demand of conventional capacity. Therefore the time series of load that has to be covered by conventional power plants is analysed with and without the supported renewable electricity generation. In this case the avoided demand for conventional capacity reaches ca. 5 GW for the year 2006.

The next step is the analysis of the monetary value of avoided capacity demand for conventional generation capacity in the year 2006. Therefore it is necessary to determine what kind of investments in generation capacity has been avoided up to 2006. If gas turbines as the cheapest technology in terms of investment are applied, the avoided investment amounts to 1.3 billion Euro[12] for 5 GW of avoided capacity. If the gas fired combined cycle plants are applied as avoided reference plant, the value almost doubles[13]. However, since the PowerACE simulation for the year 2006 without the supported renewable electricity generation shows no system outages due to shortage of capacity, it could be stated that no investments in conventional generation capacity have been replaced so far. However, a comparison of system load and available generation capacity in the given simulation run shows that this situation might change in the near future, especially if some of the older plants are decommissioned within the next years. As the analysis of the impact of renewable electricity generation on the electricity sector carried out in this chapter focuses on the year 2006, the value of the avoided investments in conventional generation capacity is set to zero.

In addition to the discussed aspects it is also likely that the increasing renewable electricity generation also has an impact on future investment decisions and the preferred plant type as the utilization of conventional plants is likely to decrease. However, this aspect goes beyond the scope of this thesis and cannot be analysed in more detail in this context.

6.4 Summary and analysis of the impact on different players

The central goal of this chapter is the assessment and quantification of the most important impacts of the supported renewable electricity generation on the electricity sector. As the previous sections have discussed a number of effects, it seems to be useful to summarize the major impacts in monetary terms. The analysis carried out in this chapter has shown that the discussed effects have considerable differences in the monetary volume. Some effects such as the merit-order effect or the lost profits of generation companies reach volumes of several billion Euro for the year 2006. Despite their considerable volume they have not yet been part of the public debate on the renewable support scheme. Other aspects such as grid extensions and cost for the balancing of the system have attracted far more public attention although the volume in monetary terms is more than factor ten smaller than the volume of the effects stated above. An overview of the results is given in Figure 6-22 and Table 6-19.

Another aspect which has to be taken into account is the evaluation of the uncertainty connected to the quantification of the effects discussed in this chapter. Some effects like the volume of the support payments and the value of renewable electricity generation can be determined in a straightforward way without major uncertainty regarding the methodology and the underlying data set. In other cases the situation is different due to limited data availability or the lack of comparable studies. Therefore it seems to be reasonable to provide an assessment of the uncertainty in addition to the provided result. In order to provide guidance for the evaluation of the results four categories ranging from low uncertainty to very high uncertainty are applied. The category of low uncertainty has already been described above. The medium uncertainty is made up by aspects such as the cost of the necessary grid extensions and the

12 Price for a gas turbine 270 Euro/kW (Sensfuß, 2004, p.67)

13 Minimum price for a combined cycle plant 450 Euro/KW (Sensfuß, 2004, p.66)

cost of the profile services that can be analysed based on existing literature and existing data. Although there is still some uncertainty connected with estimations due to the limitations of the available studies and data set, it is not likely that the actual situation varies heavily from the values stated in this thesis. The next category is made up by the issues such as the merit-order effect and the lost profit of generation companies. These aspects have not yet been part of a major scientific debate and the results are rather sensitive to the underlying assumptions. An example for such an assumption is the assumption that the simulated spot market price is the leading indicator of all electricity trades. The last category is made up by the issues related to the value and the price effect of the CO_2 emissions avoided by renewable electricity generation. Due to the very complex market situation with a remarkable drop in market prices and the scarce data on alternative saving options these results are connected with high uncertainty. But besides this uncertainty concerning the price effect the analysis of alternative CO_2 saving measures shows that the renewable electricity generation plays an important role for the reduction of CO_2 emissions which cannot easily be replaced by measures within the German sectors taking part in the emission trading scheme.

In addition to the presentation of the results in Figure 6-22 the results are also presented as numbers in Table 6-19. The presentation in Table 6-19 also contains a qualitative statement on the position of the estimated volumes as a high, medium or low end estimation. The categorization of each effect is mainly based on an evaluation of the underlying assumptions for the calculation of the effect.

Another interesting issue in the context of the analysis of the impact of renewable electricity generation is the impact of the discussed effects on the different players. In order to provide a basis for the analysis four types of players are defined: consumers, grid operators, generation companies owning generation capacity and suppliers that buy electricity and sell it to consumers. These types of players are stylized types in order to keep the analysis manageable. In the real world some players such as the four big public utilities represent a mixture of these categories since they own generation companies, sell electricity to consumers and own parts of the electricity grid.

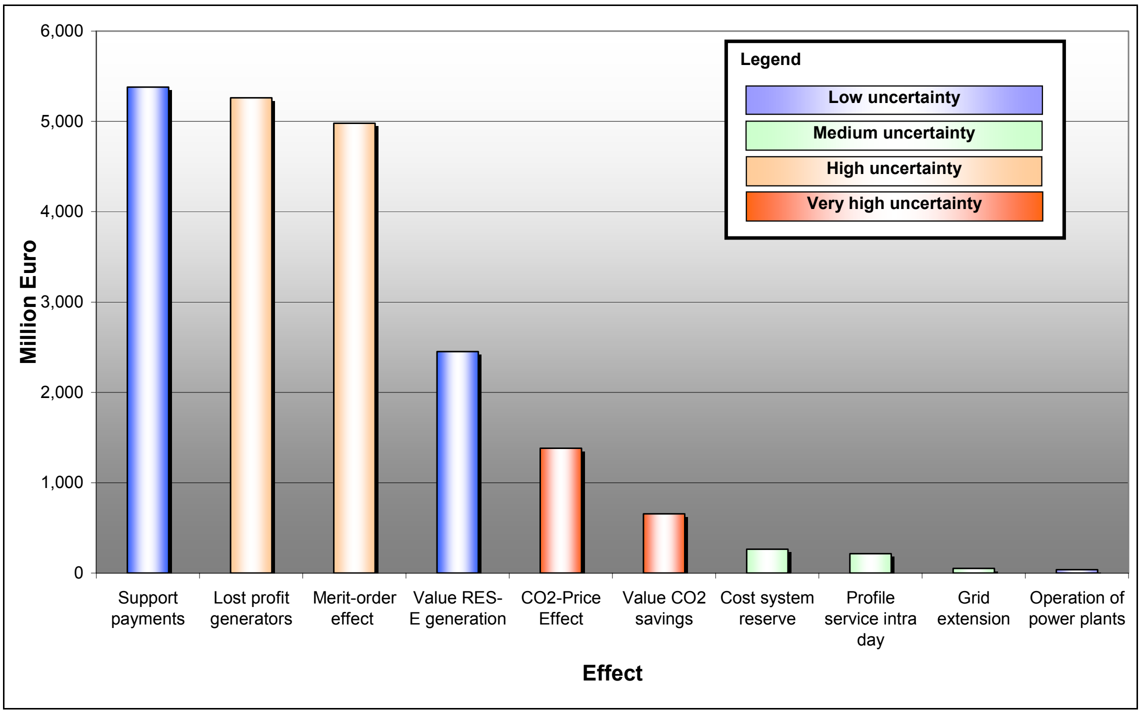


Figure 6-22: Overview of the major impacts of renewable generation on the electricity sector for the year 2006

Source: own illustration

Table 6-19: Overview of the major impacts of renewable generation on the electricity sector for the year 2006

Effect	**Volume** Million €	**Uncertainty**	**Appraisal of the estimation**
Support payments	5,380	Low	–
Lost profit generators	5,260	High	medium
Merit-order effect	4,980	High	medium
Value of RES-E generation	2,540	Low	–
CO_2 price effect	1,380	Very high	low end estimation
Value CO_2 savings	655	Very high	medium
Cost reserve capacity & energy	253	Medium	high end estimation
Profile service intra-day	215	Medium	medium
Grid extension	52	Low	high end estimation
Operation of power plants	38	Medium	high end estimation

An overview of the analysed flows is given in Figure 6-23.

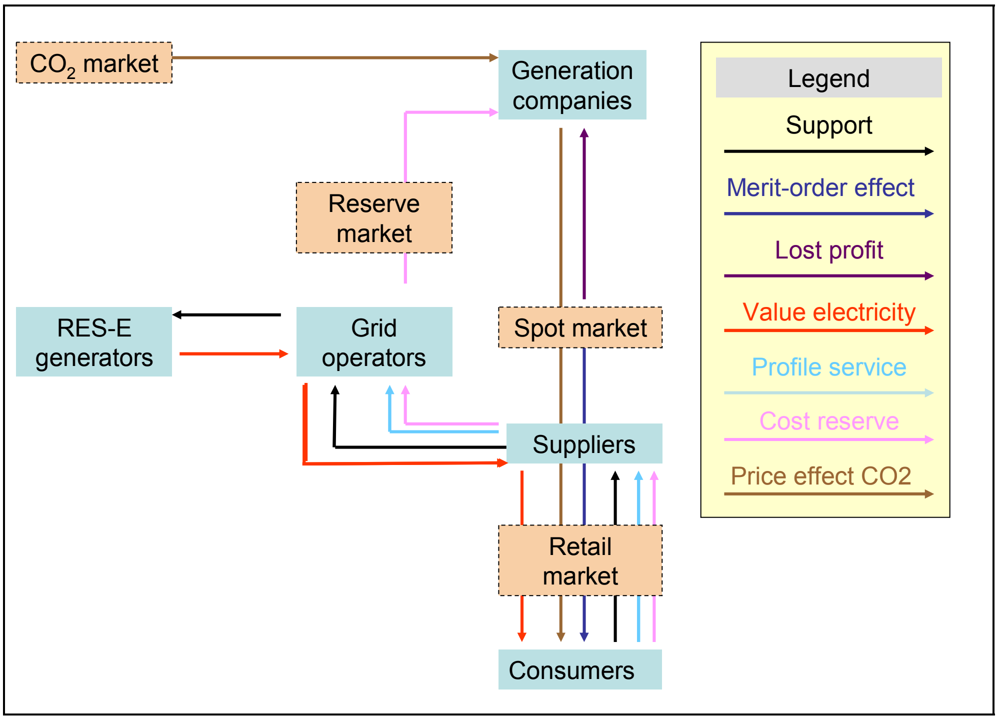


Figure 6-23: Overview of the flows of the analysed effects
Source: own illustration

One of the most important flows is the flow of the support payment. The grid operators purchase the electricity generated by renewable energy sources at defined feed-in tariffs. The purchased electricity and the cost of these payments are passed on to the suppliers. In the end these costs are passed on to the consumers. Whether the suppliers are capable to pass on the full cost of the support payments to the consumers depends on the market situation on the retail market. The same situation exists for the actual value of renewable electricity generation. The electricity is passed on as a base load block to the suppliers, which reduces the necessary electricity purchases of suppliers. Depending on the market situation, these savings are passed on to the consumers. In order to deal with prognosis errors of renewable electricity generation the grid operators have to provide a profile service in order to deliver a constant base load block to the suppliers. The resulting costs are passed on by the grid operation fees to the suppliers and finally to the consumers. A similar procedure is applied to the additional reserve capacity. In order to deal with the fluctuation of renewable electricity generation in the very short-term, grid operators have to purchase additional reserve capacity on the reserve market, which creates an additional income for the generators. The costs of the reserve capacity are integrated into the grid operation fees and passed on to the suppliers. In case of the merit-order effect the situation is more complex. The merit-order effect reduces wholesale prices for electricity. Reduced wholesale prices create savings for the suppliers purchasing electricity. Whether the full amount of the merit-order effect is passed on to the consumers depends again on the competitiveness of the retail market. On the other hand the reduced market volume to be covered by conventional power plants and the reduced spot market prices reduce the income of generation companies leading to a loss of profit. The distribution of the CO_2 price effect of renewable electricity generation is similar to the merit-order effect. If it is assumed that the overall targets for CO_2 emissions are independent of the renewable electricity generation, the renewable electricity generation reduces the prices on the CO_2 market. Lower prices on the CO_2 market lead to lower generation cost for generation companies. In case of a competitive electricity market this cost reduction leads to lower prices in the wholesale electricity market. Again the reduced wholesale prices create savings for the suppliers purchasing electricity. Similar to the merit-order effect the competitiveness on the retail market determines whether the CO_2 price effect is passed on to the consumers.

In a last step it seems to be interesting to analyse the discussed effects from a player's perspective. Thereby it is assumed that the grid operator is a neutral player which passes on its cost to the suppliers. An overview of the results is given in Table 6-20. The analysis shows that the lost profit for the generators caused by renewable electricity generation is likely to outweigh all potential income generated by other effects caused by renewable electricity generation in a competitive market. The contrary situation occurs for consumers and suppliers. The savings created by renewable electricity generation have the potential to outweigh the cost by ca. 3 billion Euro. The distribution of the possible net profit depends on the market power on the retail market.

The results indicate that suppliers and consumers that have to bear the actual cost of the support scheme profit heavily from virtual savings created by the renewable support scheme. Since the calculated virtual savings amount to a considerable volume, these aspects should gain more attention in the scientific debate. The foregone profits of generation companies also reach a considerable volume. However, high profits of the German utilities such as Eon with a profit of 8.4 billion Euro in the year 2006 (WDR, 2007) indicate that the loss of profits caused by renewable electricity generation does not endanger the profitability of conventional electricity generation within the current framework conditions. Thereby it has to be taken into account that the big utilities represent several of the stylized players such as generation companies and suppliers. In addition it has to be taken into account that utilities can also invest in renewable electricity generation in order to profit from the support payments. However, it has to stated that the resulting long-term effects on market structure and market efficieny are not analysed in this study. But the volume of the discussed effects clearly indicates that such an analysis could be important. Another important issue which has to be taken into account for the evaluation of the results is that the electricity market is not limited to Germany. Effects like the merit-order effect can also interact with the market situation in other countries. For more detailed analysis of the international interactions of these effects an extension of the developed model to a European scale is necessary.

Table 6-20: Possible net effect of the discussed effects on different players

Category effect	**Generation com-panies volume**	**Renewable generators volume**	**Supplier ⇔ Consumer volume**
	Million € 2006		
Lost profit generators	-5,260		
Support payments		5,380	-5,380
Merit-order effect			4,980
Value RES-E generation			2,540
CO_2 price effect			1,380
Value CO_2 savings	655		
Cost system reserve*	253		-253
Profile service intra day*	215		-215
Grid extension			-52
Operation of power plants	-38		
Possible total net effect	**-4,643**	**5,380**	**3,000**

* These effects represent additional turn over not profits, therfore excluded from the sum
Legend: (-) negative effect (losses) (+) positive effect

7 Additional case studies with the PowerACE Cluster System

The goal of this chapter is to present some additional case studies which show the flexibility of the developed simulation platform. Although they do not contribute directly to the analysis of the impact of renewable electricity generation on the electricity sector, they can provide interesting insights and show some possibilities for the future development of the model. These case studies extend different parts of the developed module and introduce new methodological aspects such as learning agents. The first case study applies the developed module for the agent-based simulation of the electricity demand for the analysis of price developments on the retail market. From a methodological perspective this extension of the developed module is interesting as it simulates the interaction of learning supplier agents with consumer agents. The second case study applies the developed algorithm for the optimization of pump storage power plants for the assessment of the potential income that can be generated on the spot and reserve markets by the utilization of load management. The last case study develops a new algorithm for the dynamic simulation of the construction of renewable generation capacity based on the example of wind energy. Thereby an important aspect is that the players' perspective of several players involved in investment in renewable generation capacity is integrated.

7.1 Simulation of the electricity market for private consumption

The liberalization of the electricity markets in Germany has also affected the electricity market for private consumption. However, after a short period of decreasing prices the development of electricity prices for private consumers shows a continuous upward development. Possible reasons for the rising prices on the retail market can be increasing wholesale prices for electricity or limited competition on the market. This section presents an extension of the PowerACE module for the simulation of electricity demand. The developed agent-based simulation platform is used for a case study which analyses the impact of consumer behaviour on the development of prices in the electricity market for private consumption. A detailed representation of the developed model can also be found in Müller et al. (Müller, 2003; Müller et al., 2007).

7.1.1 Description of the developed module

The developed simulation of consumer contract choice is inspired by a model presented by Widergren et al. (Widergren et al., 2004). Contract choice is simulated as a stepwise process. The first step of the simulation is to check for an external stimulus (e. g. a bill). In the simulation the stimulus is determined by a random variable which leads to an average of one stimulus per year. The second step is the question whether there is a motivation to engage in the retail market. A motivation is given if the perceived savings of a contract change exceed the expected switching costs. In order to decide on the motivation, the consumer compares the contracts of suppliers he knows. In order to reflect the uncertainty an estimation bias τ is added to the comparison. If a motivation is given, the consumer searches the market for alternative contract offers. Based on the perfect knowledge of existing contract offers on the market, the consumer again compares the savings of contract change with the perceived cost and decides whether to switch his electricity supplier. The algorithm stops if any of the checks (stimulus, motivation, comparison of cost and savings) has a negative result. The main parameters that determine the market behaviour of household agents are the estimation bias and the number of known suppliers. For the calibration of the model it is assumed that both parameters are linked by the linking parameter α. A crucial issue for the development and calibration of the model is that empirical data on consumer behaviour in the electricity market is scarce. Published switching rates are the most important indicators for the market development. An overview of the applied equations is given in Formula 7-2.

The remaining parameter that has to be determined in a calibration procedure is the parameter v. In order to calibrate the household behaviour a time series is constructed. Five suppliers offer prices for five years. The time series presented in Figure 7-1 reflects the approximate real world development after the liberalization with a high price span at the beginning of the period and higher prices with a lower price span at the end of the period. The market behaviour of consumers is calibrated by adjusting the estimation bias and the number of suppliers known to each consumer. The goal of the calibration procedure is to match the overall switching rate of 5 % of the entire period and the annual rate in order to reflect market dynamics. A comparison of the real world switching rate and the simulated switching rate for a parameter value of $v=1.3$ is presented in Figure 7-1.

Although the comparison of the switching rate shows some small differences, it can be assumed that the calibrated simulation is capable to reproduce real world market developments.

Formula 7-1: Mathematical representation of simulation and initialization of household agents

1. Estimation of the savings of a contract change

$$s_j = \left(c_j - \min\{p_i\}\right) \cdot \tau_j$$

2. Calculation of the linking parameter

$$\alpha_j = e^{\left(v \cdot \left(\frac{j}{n} - 1\right)\right)}$$

3. The estimation bias variable τ is defined by a normal distribution

$$\tau_j = \begin{cases} N(\alpha_j, 1-\alpha_j) & \text{if } N(\alpha_j, 1-\alpha_j) > 0 \\ 0 & \text{if } N(\alpha_j, 1-\alpha_j) \leq 0 \end{cases}$$

4. Probability that the supplier i is known to the agent

$$P_j(i) = \alpha_j$$

Legend:

Variables			Unit	Indices		
α	=	Linking parameter	[None]	i	=	Index of the supplier
c	=	Price of current contract	[Euro/MWh]	j	=	Index of agent
n	=	Number of consumer agents	[None]			
N	=	Normal distribution	[None]			
p	=	Price of the contract	[Euro/MWh]			
P	=	Probability that supplier is known	[%]			
s	=	Estimated savings	[Euro/MWh]			
τ	=	Estimation bias	[None]			
v	=	Market pressure parameter for calibration	[None]			

Another important step for the simulation of the electricity market for private consumption is the simulation of the behaviour of electricity suppliers.Thereby a central problem is that data on the strategic decisions and the behaviour of suppliers is not available. Therefore assumptions on the strategic behaviour of these companies are necessary. Since electricity suppliers are private companies, the assumption that suppliers act as profit maximizing companies seems to be an adequate assumption since profit maximization is a common principle in economic theory (see also Varian, 1999, p. 307ff.). The competition at the beginning of the liberalization with very low prices shows that the market share is also an important aspect for the market behaviour of a company. In order to integrate this issue into the simulation the goal of profit maximization is constrained by the requirement of a minimal market share. Since prices seem to be the most important reason for the switch of the supplier (Promit and Verband der Elektrizitätswirtschaft, 2002; Promit and Verband der Elektrizitätswirtschaft, 2003; Promit and Verband der Elektrizitätswirtschaft, 2004), competition is simulated by pricing decisions of the suppliers.

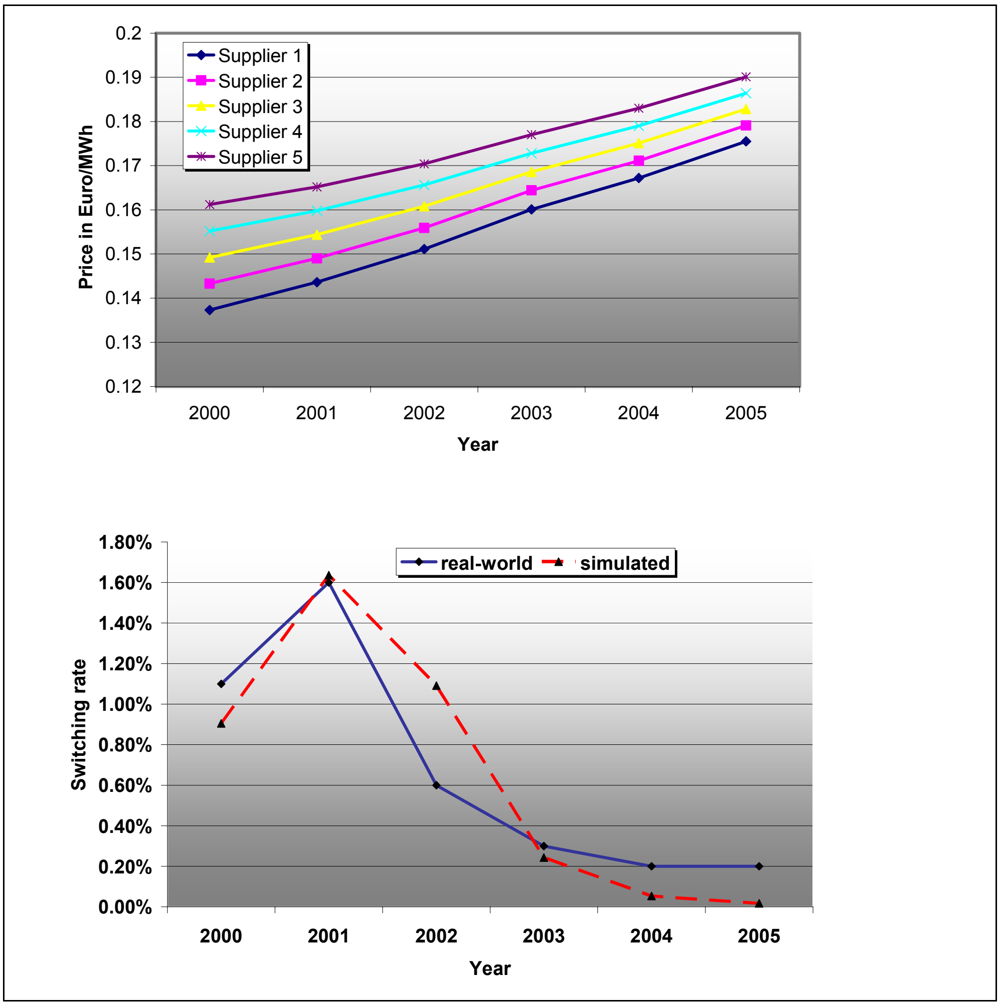


Figure 7-1: Developed price series and comparison of the simulated switching rate

Sources: Constructed price series based on Bundesministerium für Wirtschaft und Technologie [BMWI], 2007a; Stiftung Warentest, 1999; Stiftung Warentest, 2003a; Stiftung Warentest, 2003b; Verivox, 2005. Switching rate: Promit, Verband der Elektrizitätswirtschaft, 2002; Promit, Verband der Elektrizitätswirtschaft, 2003; Promit, Verband der Elektrizitätswirtschaft, 2004.
Note: Since ca. 1 % of the consumer switched their supplier in the period 1998 to 1999, this value is subtracted from the simulated switching rate of the year 2001

In order to calculate the profit a cost level of 12 cent/kWh[14] is assumed for the calculations in the simulation experiment carried out in this thesis. The market for private consumption is simulated in time steps. In each time step the suppliers decide on their prices for the next round based on the results of the last round. Each supplier has seven strategies available: extreme price increase or decrease (1 cent/kWh), moderate increase or decrease (0.5 cent/kWh), very moderate increase or decrease (0.2 cent/kWh) and no price change. In order to simulate price developments within the market suppliers are endowed with a simple reinforcement algorithm based on the algorithm developed by Roth and Erev (Roth and Erev, 1995). At the beginning each supplier randomly chooses its strategy. After one round the pay-off of a given strategy is evaluated with regard to the development. The probability of a successful strategy is increased while the weight of an unsuccessful strategy is decreased. If the restriction of the

14 Average price of the year 2000 (Bundesministerium für Wirtschaft und Technologie [BMWI], 2007a)

minimal market share is violated, the weight of the strategy which has led to the violation of the minimal market is share set to zero.

Strategies with a probability of less than 0.1 % are eliminated. Learning stops when the probability of each strategy changes for less than 0.1 %. If learning is finished, the supplier sets its price and the consumer algorithm is started. Thereafter the suppliers evaluate their strategy and learning starts again. The described cycle is repeated until a given number of steps is reached. It has to be taken into account that the success of a strategy also depends on the strategies of the competitors. Therefore the learning algorithm helps the suppliers to adjust to a competitive environment. An overview of the developed algorithm is given in Figure 7-2.

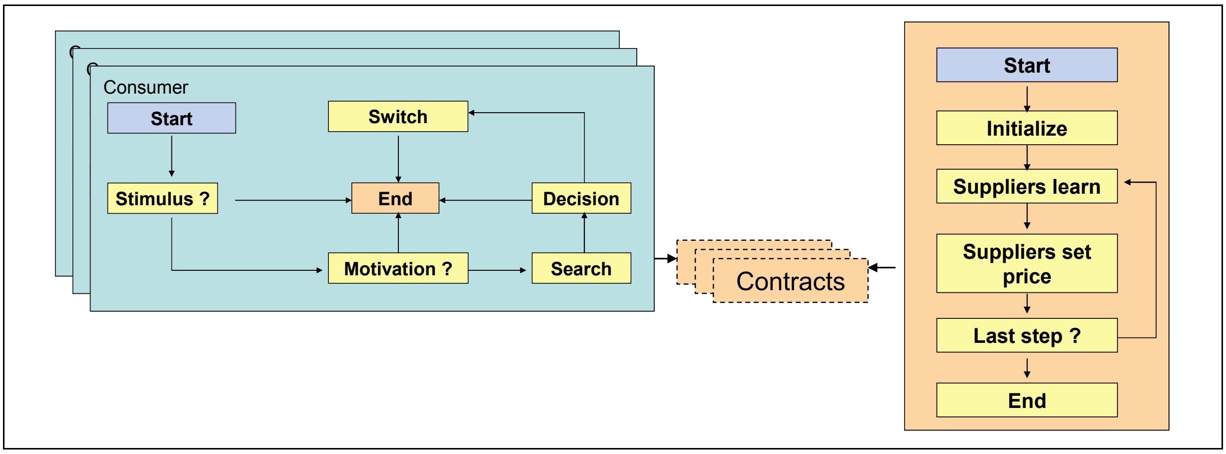


Figure 7-2: Structure of the simulation of prices on the market for private consumers
Source: own illustration

A mathematical formulation of the developed algorithm for supplier agents is given in Formula 7-2.

Formula 7-2: Mathematical representation of the pricing decision of a supplier agent

1. Determine the pricing strategy:

a) Definition of profit

$$p(t) = (o - k) \cdot d$$

b) Determine the pay-off of the last pricing strategy

$$x(t) = \frac{p(t) - p(t-1)}{p(t-1)}$$

c) Update weight of each strategy

$Q = \{q_1, ..., q_7\}$; Initial value: $\{\frac{5}{7}, \frac{5}{7}, ..., \frac{5}{7}\}$ (determined by calibration)

$S = \{s_1, ..., s_7\}$; Initial value: $\{\frac{1}{7}, \frac{1}{7}, ..., \frac{1}{7}\}$

c1) $q_i(t) = q_i(t-1) + x(t)$

c2) $s_i(t) = \frac{q_i(t)}{\sum_j q_j(t)}$

d) Determine the value of the pricing strategy

$$C = \{c_1, ..., c_7\} = \{-1, -0.5, -0.2, 0, 0.2, 0.5, 1\}$$

$$c = \begin{cases} c_1 & if \quad 0 < r \le s(1) \\ c_i & if \quad \sum_1^{i-1} s(i) < r \le \sum_1^{i} s(i) \\ ..... & \\ c_7 & if \quad \sum_{i=1}^{6} s(i) < r \le \sum_{i=1}^{7} s(i) \end{cases}$$

2) Determine the price

$$o(t) = o(t-1) + c$$

Legend:

Variables			Unit
C	=	Collection of strategies	[None]
c	=	Pricing strategy	[Cent/kWh]
d	=	Contracted consumption	[kWh]
k	=	Cost	[Euro]
o	=	Price	[Cent/kWh]
p	=	Profit	[Euro]
Q	=	Collection of propensities	[None]
q	=	Propensity of each strategy	[None]
r	=	Random number	[None]
S	=	Collection of probabilities	[None]
s	=	Probability of each strategy	[None]
t	=	Time step	[None]
x	=	Pay-off	[Euro]

Indices		
i	=	Index of strategy
j	=	Index of strategy

7.1.2 Case study

In order to analyse the market situation in the market for private electricity consumption, a case study is carried out with the developed model. The simulation is made up of 5000 household agents and five suppliers. The number of 5000 households is selected because the number is high enough to avoid strong influences of single consumers and low enough to keep the demand for computational resources at an adequate level. Each supplier starts with 1000 customers and an initial price which is based on the price for the year 2000 presented in Figure 7-1. After the initialization the learning phase begins. Once the learning is finished, each supplier sets its price. The consumers decide on a change of their supplier. This simulation assumes that a stimulus is always given. Thereafter the learning process of suppliers starts again and the procedure is repeated until 500 steps are reached.

The simulation experiment is carried out with the market behaviour of household consumers based on the calibration procedure presented above. The simulation experiment is repeated 100 times and the average price development is calculated. The results are presented in Figure 7-3. The figure shows two important phenomena. Prices increase heavily until they stabilize at a very high level and the prices of the suppliers evolve in a narrow price band. Both phenomena can also be observed in the real world.

In order to analyse the sensibility of the results to the underlying parameters, the parameters of minimal market share and market pressure are varied in additional simulation experiments. Table 7-1 gives an overview of the results. For a broad parameter range the resulting market prices end up considerably above the minimum cost of 12 cent/kWh.

Table 7-1: Results of the parameter variation

Market pressure variable	**Suppliers known in average**	**Minimal market share (in % of initial market share)**						
		70	**75**	**80**	**85**	**90**	**95**	**99**
		average price (cent/kWh) / average price span (cent/kWh)						
0.2	4.6	16.6 / 1.5	16.2 / 1.3	15.7 / 1.1	14.9 / 0.77	13.1 / 0.7	12.7 / 0.8	12.4 / 0.8
0.4	4.3	17.9 / 1.8	17.4 / 1.6	16.8 / 1.3	16.1 / 0.97	13.9 / 0.6	12.7 / 0.7	12.4 / 0.7
0.7	4	20.5 / 2.4	19.6 / 2.0	18.9 / 1.7	18.1 / 1.3	16.6 / 0.8	12.8 / 0.6	12.4 / 0.7
1	3.9	24.4 / 3.0	22.6 / 2.5	21.3 / 2.0	20.1 / 1.6	18.7 / 1.1	13.1 / 0.6	12.4 / 0.6
1.3	3.2	30.8 / 3.8	26.8 / 3.0	24.2 / 2.4	22.5 / 1.9	20.7 / 1.3	14.5 / 0.6	12.4 / 0.6
1.6	3	42.9 / 5.3	33.5 / 3.8	28.4 / 2.9	25.3 / 2.2	23.1 / 1.5	17.9 / 0.7	12.5 / 0.6

Legend:
Price above initial price (green); Price above cost (blue); Basic scenario (orange)

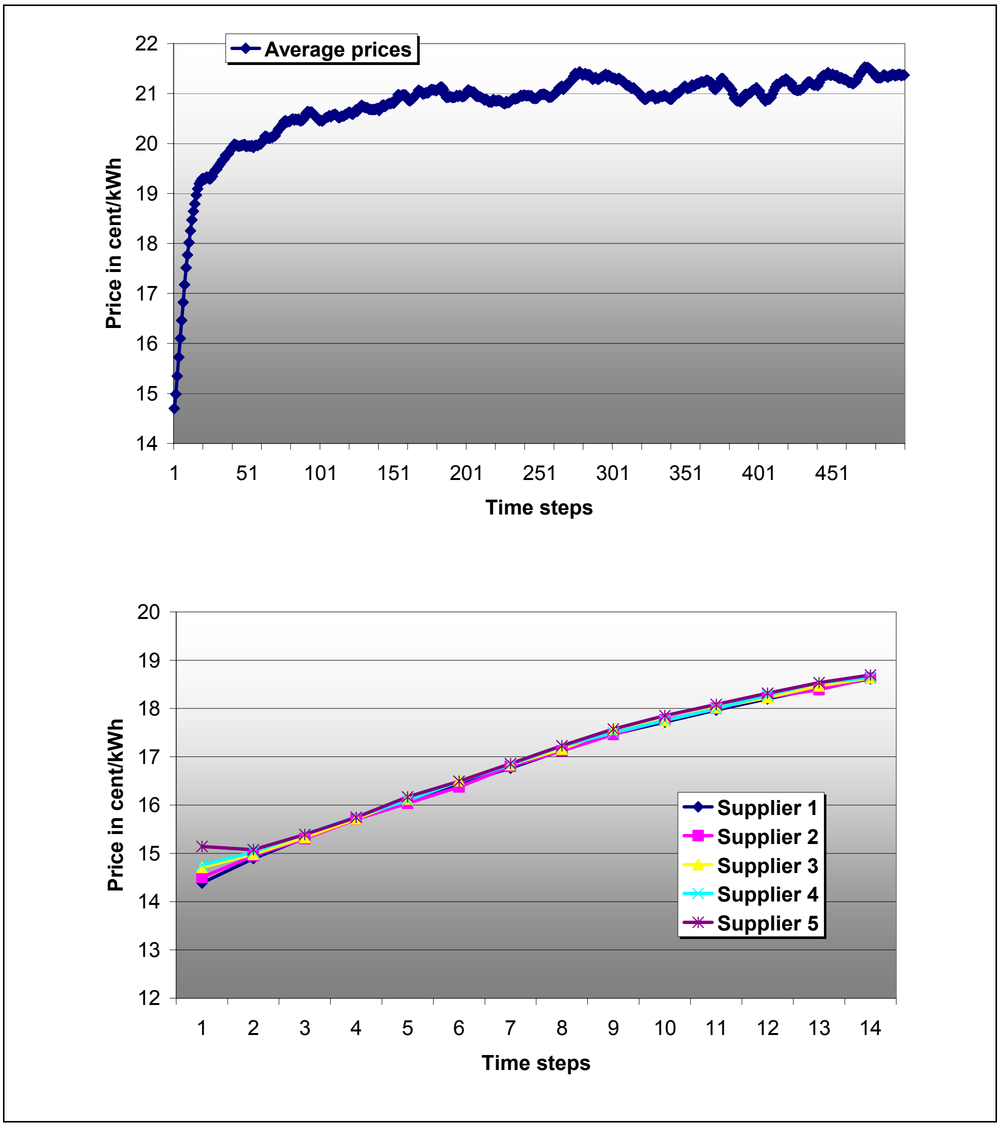


Figure 7-3: Simulation results: Average price development

Source: own illustration

The results of the case study indicate that with the existing low market pressure of private customers and moderate market share requirements of the suppliers prices tend to increase. It is important to state that no collusion between the suppliers or an increased cost level is required to reach this result. This may provide important insights for the political debate on the liberalization process. The goal of increased competitiveness and lower prices is likely to be missed if market pressure stays at a low level in Germany.

7.1.3 Summary and outlook

This section presents a first version of an agent-based simulation of the electricity market for private consumption. While suppliers are modelled as profit maximizing companies, consumer behaviour is calibrated against the scarce existing data. Based on the calibrated model, a case study is carried out to simulate the electricity market for private consumption in Germany. The results indicate that market participation and market pressure of household consumers may be too low to keep electricity prices on a low level. The crucial issue for a more detailed in-depth analysis of the electricity market for private consumption is the problem that data on household behaviour and strategic market decisions of suppliers is scarce. Rising prices in the real world are not only influenced by the market development on the market for private consumption, but also by rising prices on the wholesale market and the political situation which may influence pricing decisions of suppliers. Nevertheless the developed model can provide some interesting insights into the market dynamics of the electricity market for private consumption and its lack of market pressure. Future work could be directed to a more detailed analysis of household behaviour, a more detailed representation of pricing decisions of suppliers and the integration of market segments such as "green" electricity contracts selling electricity generated by renewable energy sources.

7.2 Assessing the potential income for load management on the spot market

The rapid development of fluctuating renewable electricity generation has increased public interest in load management as an important option to deal with fluctuating generation in order to manage the electricity grid. This case study takes a different perspective by analysing the potential income that can be generated by load management on the different electricity markets in Germany. The potential income represents the upper boundary for the cost of the implementation of load management such as communication infrastructure and management.

7.2.1 Characteristics of the load management potential

The technical characteristics of the analysed load management options in this study are based on data published by Klobasa et al. (Klobasa et al., 2007; Klobasa and Ragwitz, 2005b). The applied data set focuses on the industry and the household sector. Important characteristics for the assessment of load management options are the unit size and the maximum number of hours the load of the application can be moved. Since the minimum time horizon on the spot market is one hour, adjustments are necessary in cases where the application can only be moved for less than one hour. In these cases it is assumed that a pool of the electric devices can reach a movement of one hour by sequential load reduction of parts of the pool. But in these cases the average available unit size of a technology is reduced correspondingly. Examples are cooking devices where it cannot be assumed that the load can be moved for one hour. Other important assumptions are the efficiency of the load management measures in terms of energy losses and the maximum number of times per year a given application can be utilized for load management. This is especially important for industrial applications where the main purpose is the production of a good. An overview of the key characteristics of the analysed load management options is given in Table 7-2.

Table 7-2: Key characteristics of the analysed load management potential

Branch	Technolgy	Capacity (MW)	Unit size* (MW)	Maximum delay in hours	Maximum number of movements	Efficiency** (%)
Chemicals	Chlorine Electrolysis	260	14	4	20	95
Paper	Papermachine	100	2	4	20	95
Paper	Roll compaction	60	1	1	20	95
Paper	Refiner	400	10	8	40	98
Paper	Preparation	250	1	2	20	95
Non-ferrous metals	Aluminium-Elektrolysis	300	10	4	20	95
Non-ferrous metals	Copper	7.5	1	4	20	95
Iron and steel	Steel oven	400	30	4	20	100
Cement	Mills	180	2	8	40	100
Households	Washing machine	487	0.000033	24	8,760	100
Households	Dish washer	427	0.000031	24	8,760	100
Households	Dryer	538	0.000374	24	8,760	100
Households	Refrigerator	353	0.000027	1	8,760	90
Households	Refrigerator & Freezer	194	0.000033	1	8,760	90
Households	Freezer	358	0.000033	1	8,760	90
Households	Cooking	191	0.000032	1	8,760	90

* Unit size for households: average available unit size = Capacity multiplied by the utilization in % of time
** Efficiency: Electricitity consumption without one movement divided by electricity consumption with one movement

Source: Based on Klobasa et al., 2007; Klobasa and Ragwitz, 2005b

7.2.2 Methodology

This case study assesses the potential income of load management options on the spot market and on the reserve market. In order to assess the potential income on the spot market a modified version of the pump storage algorithm presented in Chapter 5 is applied. The data on the load management options is transferred to the characteristics of pump storage plants and stored in an additional database. The main modification is the calculation of the "storage volume" by multiplying the available capacity with the maximum hours of delay. In order to assess the broad range of the potential income two scenarios are developed which represent the upper and the lower range of the potential income. The Max.-Scenario represents the upper range of the potential income. The scenario utilizes the algorithm for the bid price of pump storage plants on the secondary reserve market. The price prognosis is based on the real market prices of the German spot market in the year 2005. The utilization of pump storage plants takes place with perfect knowledge of the market price of the entire year. In addition it is assumed that market prices are not affected if load management is activated. Both assumptions of perfect market knowledge and stable price which do not react to the activation of up to 4.5 GW load management potential are very optimistic. Therefore it can be stated that this scenario represents the very upper end of the possible income on the spot market. The second scenario is the Min.-Scenario. This scenario uses model based prices as input data. As described in Chapter 5, these prices are less volatile, which leads to lower income for load management. The utilization of load management measures takes place on a cost based price prognosis. In the household sector the dispatch takes place on the time horizon of 24 hours and prices are simulated dynamically which means that prices are influenced by the utilization of load management, thus reducing the potential income. In case of the industry sector the limited number of activations for load management needs to be integrated into the simulation. Therefore the dispatch takes place on the time horizon of an entire year and a cost based price prognosis. Especially the dispatch on the basis of a cost based price prognosis which is far less volatile than the real market leads to a comparatively low income for load management. Therefore the scenario can be considered to represent the lower end of the possible income. An overview of the main characteristics of the developed scenarios is given in Table 7-3.

Table 7-3: Description of the selected scenarios

	Max.-Scenario Industry-Households	**Min.-Scenario Industry**	**Min.-Scenario Households**
Prices	Real Market Prices 2005	Model-based prices	Model-based prices
Market prices	Static	Static	dynamic
Dispatch of load management	Optimized dispatch for 365 days, perfect knowledge of market prices	Optimized dispatch for 365 days, cost based price prognosis	Optimized dispatch for 24 hours, simulation for 365 days, cost based price prognosis

7.2.3 Results

The potential income that can be generated by load management is calculated as average daily income in Euro/MW and as annual income per unit. The results for the industry sector show an average daily income between 1.3 Euro/MW and 27.5 Euro/MW depending on the scenario and technology. If the income is compared to an estimation of the daily cost for load management with a limited number of movements of ca 10 Euro/MW (Klobasa et al., 2007), it is likely that some big industrial application can create profits by spot market trades based on load management. In terms of annual income per unit the income varies between several hundred and ca. 190 thousand Euro. The figures indicate that the communication infrastructure and management of the load can be feasible in some big industrial applications. The results of the household sector are different. While in most cases the calculated average daily income in Euro/MW is higher than in the industry sector, the actual income per unit is rather small. Even in the Max.-Scenario the annual income per unit reaches values between 0.40 and 3.76 Euro. An exception is the dryer which can reach a higher income due to the higher available capacity.

Other opportunities to create income by the utilization of the existing load management potential are the reserve markets (also see Chapter 5.4.2 for more details). The primary reserve market is not very attractive for load management due to technical requirements and the necessity to be able to change the load in both directions, which may not be the case for most load management options. But the secondary reserve market and the minute reserve market could be attractive for load management since positive and negative reserve are purchased by a separate tender. In order to estimate the possible income on the reserve markets the average positive capacity prices for the year 2005 are multiplied by the unit size and the number of days per year.

Table 7-4: Model results: Possible income on the spot market

Branch	**Technolgy**	**Capacity**	**Unit size***	**Min. Scenario**	**Max. Scenario**	**Min. Scenario**	**Max. Scenario**
				Daily income		**Annual income**	
		MW	MW	€/MW		€ per unit	
Chemicals	Chlorine Electrolysis	260	14	1.91	16.05	9,760	82,020
Paper	Paper-machine	100	2	1.91	16.05	1,390	11,720
Paper	Roll compac-tion	60	1	1.32	9.8	480	3,580
Paper	Refiner	400	10	4.18	26.8	15,260	97,820
Paper	Preparation	250	1	1.55	14.18	570	5,180
Non-ferrous metals	Aluminium elektrolysis	300	10	1.91	16.05	6970	58,580
Non-ferrous metals	Copper	7.5	1	1.95	16.16	710	5,900
Iron and steel	Steel oven	400	30	2.13	17.09	23,320	187,140
Cement	Mills	180	2	4.34	27.47	3,170	20,050
Households	Washing machine	487	0.000033	55.02	312.25	0.66	3.76
Households	Dish washer	427	0.000031	54.99	303.05	0.62	3.43
Households	Dryer	538	0.000374	54.5	244.09	7.44	33.32
Households	Refrigerator	353	0.000027	0	40.2	0	0.40
Households	Refrigerator & Freezer	194	0.000033	0	40.3	0	0.49
Households	Freezer	358	0,000033	0	40.2	0	0.48
Households	Cooking	191	0.000032	0	35.62	0	0.42
* Unit size for households: average available unit size = Capacity multiplied by the utilization in % of time							

The results are presented in Table 7-5. Especially the load management in the industry sector can generate considerable incomes between 78 thousand and more than two million Euro per unit and year. Additional income could be generated by the work prices. But due to the lack of data on the work prices and the actual utilization of the reserve capacity they are difficult to estimate. Even without this additional income the figures show that the reserve markets are far more attractive for industrial load management than the spot market. Especially the minute reserve market seems to be very attractive as it is characterized by a daily tender and low utilization of the reserve itself. The size of the expected income seems to be high enough to deal with the qualification procedures and the technical issues. There are already players on the market who bid load management potential into the reserve market. Again, the results for the household sector are different. Apart from dryers the possible income per unit reaches not more than ca. 3 Euro per year and unit. These figures show that the cost of the communication infrastructure and the management of the applications need to be very cheap in order to be profitable. This is mainly caused by the low available capacity per unit. Bigger applications in the service sector could be more attractive.

Table 7-5: Estimated income on the reserve markets

Branch	Technolgy	Capacity	Unit size*	Minute reserve market	Secondary reserve market	Minute reserve market	Secondary reserve market
				Capacity price		Annual income	
		MW	MW	€/(MW day)		€ per unit	
Chemicals	Chlorine Electrolysis	260	14	215	250	1,098,650	1,277,500
Paper	Paper-machine	100	2	215	250	156,950	182,500
Paper	Roll compaction	60	1	215	250	78,475	91,250
Paper	Refiner	400	10	215	250	784,750	912,500
Paper	Preparation	250	1	215	250	78,475	91,250
Non-ferrous metals	Aluminium elektrolysis	300	10	215	250	784,750	912,500
Non-ferrous metals	Copper	7.5	1	215	250	78,475	91,250
Iron and steel	Steel oven	400	30	215	250	2,354,250	2,737,500
Cement	Mills	180	2	215	250	156,950	182,500
Households	Washing machine	487	0.000033	215	250	2.59	3.01
Households	Dish washer	427	0.000031	215	250	2.43	2.83
Households	Dryer	538	0.000374	215	250	29.35	34.13
Households	Refrigerator	353	0.000027	215	250	2.12	2.46
Households	Refrigerator & Freezer	194	0.000033	215	250	2.59	3.01
Households	Freezer	358	0.000033	215	250	2.59	3.01
Households	Cooking	191	0.000032	215	250	2.51	2.92
* Unit size for households: average available unit size = Capacity multiplied by the utilization in % of time							

Source: Own calculations based on: RWE Transportnetz Strom, 2006; E.ON Netz, 2006;EnBW Transportnetze AG, 2006;Vattenfall Europe Transmission, 2006)

7.2.4 Summary and outlook

This case study presents an estimation of the potential income of load management options based on the market situation in year 2005. The estimation of the spot market income by means of the developed simulation platform PowerACE and its pump storage algorithm shows the flexibility of the developed model. The analysis shows that the industry sector is the most attractive sector for load management while the potential income in the household sector is rather low. A comparison between the expected income on spot and reserve markets shows that the reserve markets are far more attractive for industrial load management. An interesting extension of this case study could be the analysis of load management options in the service sector. If prices tend to become more volatile, it could also be useful to repeat this case study for other years since higher volatility is likely to lead to higher income for storage options or load management.

7.3 Simulating the expansion of renewable electricity generation in Germany

The German support scheme for electricity generation based on renewable energy sources has led to a considerable increase of renewable electricity generation in Germany, especially wind energy. But the dynamic development of wind energy in Germany also showed considerable weaknesses in the scientific capability to produce reliable projections on the future development of the installed capacity. Even optimistic projections for the development have been overtaken by the real development within one or two years. A comparison of the real development of wind energy and the projections of different studies is given in Figure 7-4.

So the central question is why these studies failed to provide an adequate projection of the development of wind energy. Most projections are based on expert judgement of the likely future potential of wind energy. The linear shape of most projections is in strong contrast to the exponential growth seen in the past. In addition to their weak projections this methodology also fails to provide insights into the impact of different support policies on the actual development of wind energy. Since the development of renewable electricity generation in Germany has reached a considerable volume and with offshore technology there is another technology with huge potential ready to take off, it seems to be necessary to consider new approaches to provide adequate estimations of the future development of renewable electricity generation for policy makers and utilities. These new approaches should also be capable to show the impact of different support schemes on the actual development.

One example of a new model developed especially for the simulation of renewable electricity generation is the Green X model. It is a simulation with an algorithm seeking to minimize the cost connected with the achievement of a given renewable electricity generation target. Thereby demand side measures and technology specific investment characteristics are taken into account (Huber et al., 2004a).

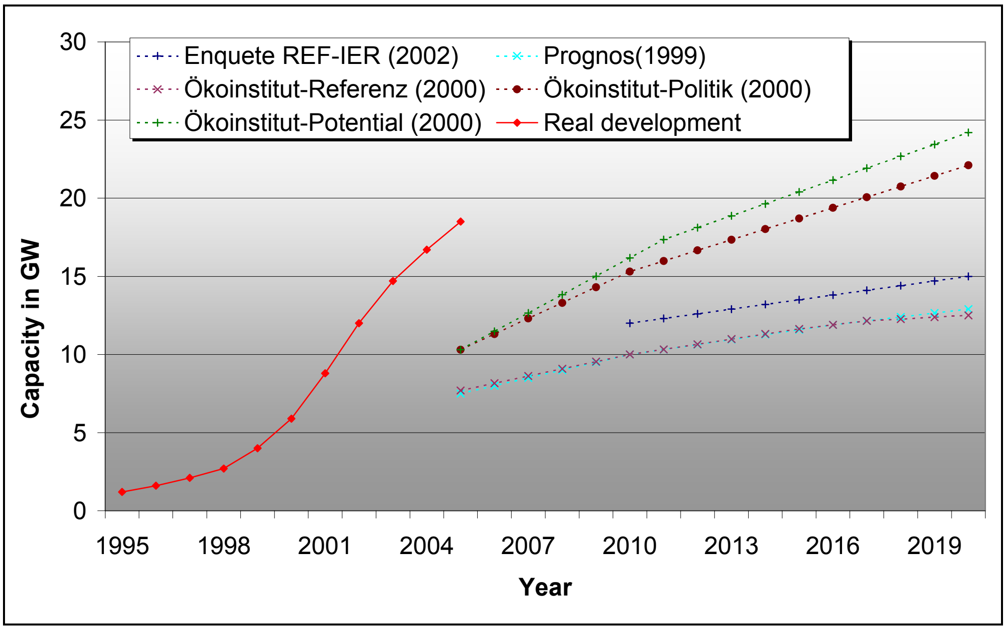


Figure 7-4: Different projections for the development of wind energy in Germany

Sources: Prognos AG and Europäisches Zentrum für Wirtschaftsforschung und Strategieberatung (ewi), 1999; Öko-Institut, 2000; Enquete Kommission, 2002

This section presents an agent-based approach to the simulation of renewable electricity generation. The integration into the larger agent-based simulation platform provides the opportunity to analyse different support schemes such as certificate systems and the impact of different developments of renewable electricity generation on the electricity markets.

7.3.1 The renewable investment module

A central basis for the simulation is a detailed database on cost potential curves of renewable electricity generation technologies in Germany. An overview of the potential curve is given in Figure 7-5.

In the given simulation platform a major player is an investment planner that determines the expected income of renewable investment options based on the available potential, the required interest rate and the available support. Based on this information, a production request is generated which contains all investment options with a positive annuity. An important parameter for the investment planner is the applied interest rate for the calculation. Based on a recent study presented by Held (Held et al., 2006), an interest rate of 6.6 % is assumed for the German feed-in system. Since the German feed-in system is based on nominal support values, the impact of inflation has to be taken into account. Based on an analysis of the development of inflation over the past 50 years, an inflation rate of 2 % is assumed (Sensfuß, 2004).

The "Renewable Energy Source-Plant Producer" builds new renewable power plants according to the available production capacity. Requests exceeding the production capacity are not fulfilled. If the requests for new plants exceed the production capacity, the plant producer considers building new production facilities based on the remaining potential for the renewable technology and its own requirements concerning the expected utilization of new production facilities. The expansion of production facilities is also limited by a maximum value representing the real world restrictions to the expansion of production facilities. In case of wind energy the maximum annual extension of production facilities is limited. Thereby the "RES-Plant producer" of the simulation is used as an aggregate for all the planning and construction capability of a country needed to carry out projects for the construction and operation of renewable power plants. Interaction with construction and planning capabilities of neighbouring countries are not taken into account in the current version of the model.

Two smaller modules seek to integrate the aspect of technology learning and the dampening effect of planning and authorization procedures. The module for technology-learning simulates the impact by adjusting the cost of renewable power plants by an annual reduction factor of 1.5 % reflecting the average annual cost reduction presumed in the Renewable Energy Source Act. In principle a technology learning based on learning curves could also be integrated, but the additional benefit is questionable as the model only simulates the German development. An adequate picture of the learning effects would require a lot of external learning which can only be integrated as external input parameter. The authorization module reflects the dampening effect if the installed capacity gets close to the limitations of the available technological potential. In reality it gets increasingly difficult to utilize the remaining potential if a large part of the generation potential is already utilized. Authorization procedures last longer and it is more difficult to discover places which are e. g. suitable for wind power plants. In the given version this aspect is integrated by two factors. The first factor determines the possible utilization of the generation potential which can take place without the dampening effect. The second parameter determines the actual dampening effect in terms of the production request sent by the investment planner. Both parameters are determined in a calibration procedure. An overview of the model structure and the applied formulas is given in Figure 7-5 and Formula 7-3.

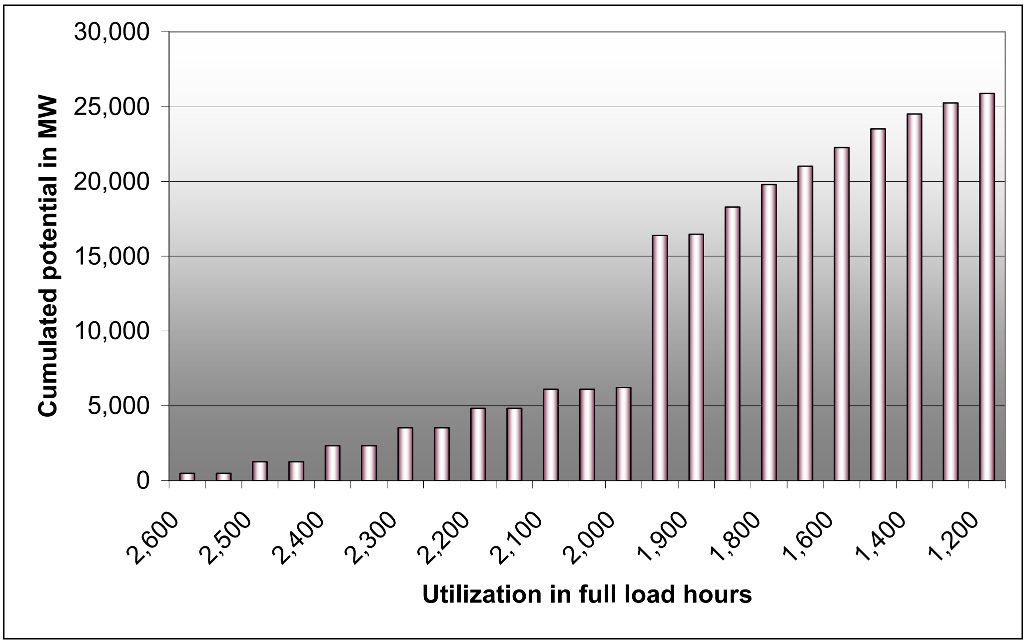


Figure 7-5: Potential curves of wind energy in Germany

Source: own illustration, data: renewable potential database of the Fraunhofer Institute for Systems and Innovation Research

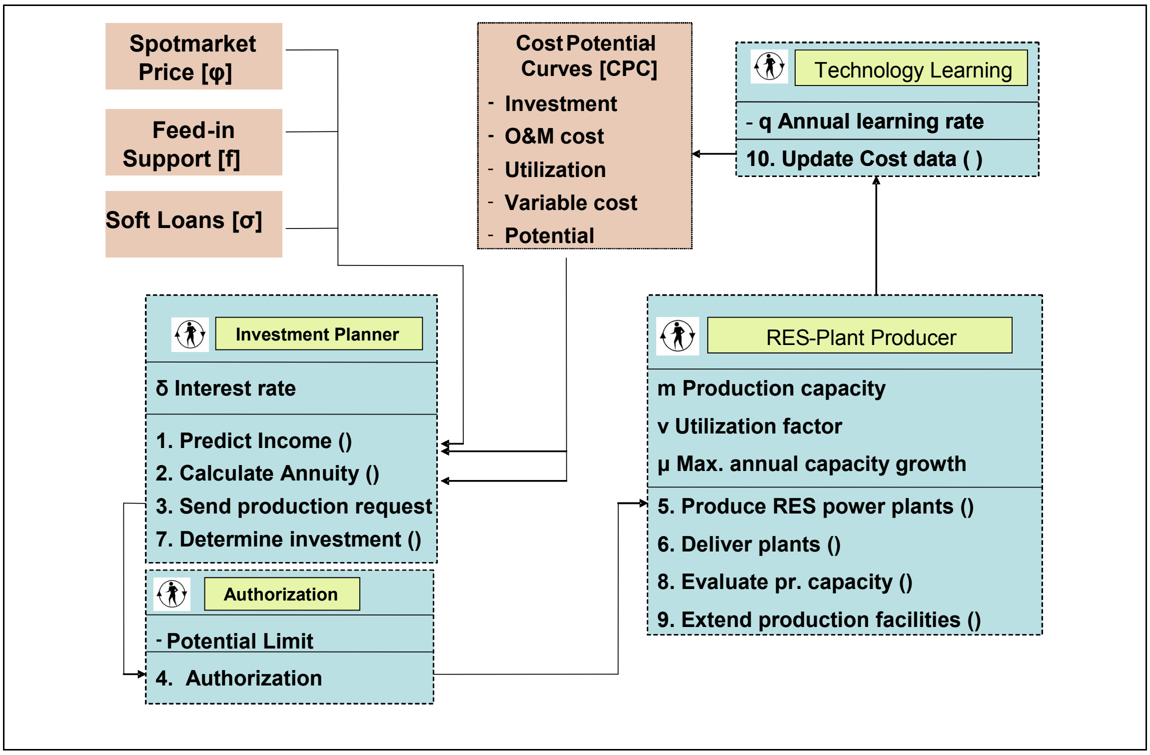


Figure 7-6: Structure of the developed simulation platform

Source: own illustration

Formula 7-3: Mathematical representation of simulation investment processes

1. Predict the annuity of the potential income of an investment option within the cost potential curve

$$x(t)=\begin{cases}\varphi(t) & if \quad \varphi(t)\geq f(t)\\ f(t) & if \quad \varphi(t)<f(t)\end{cases}$$

$$a_d(t)=\frac{\delta}{1-(1+\delta)^{-\psi}}\sum_{t=1}^{t=\psi}\left(\frac{x(t)\cdot z_d}{(1+\delta)^t}\right)$$

2. Calculate annuity of the cost

$$b_d(t)=k_d(t)\left(\sigma\cdot\frac{\delta}{1-(1+\delta)^{-\psi}}+(1-\sigma)\cdot\frac{j}{1-(1+j)^{-\psi}}\right)+c_d$$

3. Determine production request

$$r(t)=\sum_d h_d(t) \;\; if \;\; a_d(t)\geq b_d(t)$$

4. Authorization

$$s(t)=\begin{cases}r(t) & if \;\; \left(g(t-1)+r(t)\right)<p\\ r(t)\cdot\gamma & if \;\; \left(g(t-1)+r(t)\right)>p\end{cases}$$

5. - 7. Produce renewable power plants

$$g(t)=\begin{cases}g(t-1)+s & if \;\; s<m(t)\\ g(t-1)+m(t) & if \;\; s\geq m(t)\end{cases}$$

8. - 9. Extend production facility

$$m(t+1)=\begin{cases}m(t) & if\; s\leq m(t)\\ m(t)+\left(\frac{e(t)}{\nu}-m(t)\right) & if\; s>m(t)\; and\; \left(\frac{e(t)}{\nu}-m(t)\right)<\mu\\ m(t)+\mu & if\; s>m(t)\; and\; \left(\frac{e(t)}{\nu}-m(t)\right)\geq\mu\end{cases}$$

10. Update cost data

$$k(t+1)=k(t)\cdot q$$

Legend:

Variables			Unit	Indices		
a	=	Annuity of the expected income	[Euro]	t	=	Time step in years
b	=	Annuity of cost	[Euro]	d	=	Index of potential step
c	=	Variable cost of the technology	[Euro/MWh]			
e	=	Feasible potential or renewable gen. capacity	[MW]			
f	=	Feed-in tariff	[Euro/MWh]			
g	=	Installed capacity	[MW]			

h	=	Available capacity in potential step	[MW]
k	=	Investment	[Euro/MW]
l	=	Interest rate of soft loans	[%]
m	=	Maximum output of production facility	[MW]
p	=	Potential limit	[MW]
q	=	Learning factor	[None]
r		Production request	[MW]
s	=	Authorized production request	[MW]
u	=	Utilization	[Hours]
x	=	Annual income	[Euro]
γ	=	Growth damper	[None]
δ	=	Interest rate	[%]
μ	=	Maximum annual growth of the production facilities	[MW]
ν	=	Required utilization of new production facilities	[Years]
σ	=	Share of soft loans	[%]
φ	=	Projected market price for electricity	[Euro/MWh]
ψ	=	Lifetime of the technology	[Years]

7.3.2 Case Study

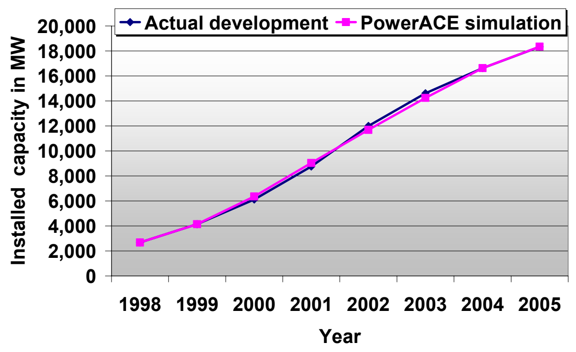
In a case study the model is applied to analyse the impact of soft loans with reduced interest rates on the development of onshore wind energy in Germany. The importance of the availability of soft loans for the development of renewable electricity generation is rarely discussed. However, an analysis of the past development shows that a considerable amount of the investment into wind energy has been financed with the help of soft loans. In 2003 ca. 81 % of the capital needed for the construction of new wind energy has been financed by soft loans of the German "KfW promotional bank" (Kreditanstalt für Wiederaufbau [KfW], 2005 found in Held, 2005).

7.3.3 Input parameters and calibration of the model

In order to be able to utilize the model for the given task, the most important input parameters for the agents involved in the simulation have to be determined. The interest rate of soft loans is assumed to be 4.40 % in accordance with information provided by the KfW-bank.

The next step is to determine the parameters of the plant producer agent. The capability of the sector to realize new wind projects in the year 1998 is assumed to be 1466 MW in compliance with the new installations of the given year. The maximum possible extension of plant production facilities is assumed to be 760 MW, which represents the maximum growth of new installed wind capacity in the period 1990-2005. The required utilization ratio of new production facilities and remaining potential is determined by a calibration run. In order to calibrate the model the development of wind energy between the period 1998 and 2005 is simulated. This period is selected due to the relatively stable support conditions in this period. All free parameters are adjusted until the simulated development is close to the real development in the given period. The calibration to the period between 1998 and 2005 shows a maximum deviation between the real development and the simulated development of the installed capacity of 370 MW. Based on this calibration the required utilization of new production facilities is assumed to be seven years.

Another important agent within the simulation is the authorization agent. The parameters of this agent are determined by the calibration run. The potential limit after which authorization procedures dampen further growth is set to 70 %. If this limit is reached, the production request sent by the investment planner is damped by the growth-damper-factor of 50 %. An overview of the calibration and the parameters is given in Figure 7-7.



Plant Producer	Value
Initial production capacity	1,466 MW
Maximum extension per year	760 MW
Required utilization of new facilities	7 years
Authorization	
Potential limit	70 %
Growth damper	50 %
Investment planner	
Required interest rate	6.60 %
Inflation	2 %
Interest rate (soft loans)	4.40 %
Share of soft loans	0/81 %

Figure 7-7: Calibration of the simulation
Source: own illustration

7.3.4 Results

The impact of loans with reduced interest rates provided by the German "KfW promotional bank" is analysed by running the model with feed-in support and a share of soft loans of 81 %. In a next step the model is run without soft loans. A comparison of both simulation runs is given in Figure 7-8.

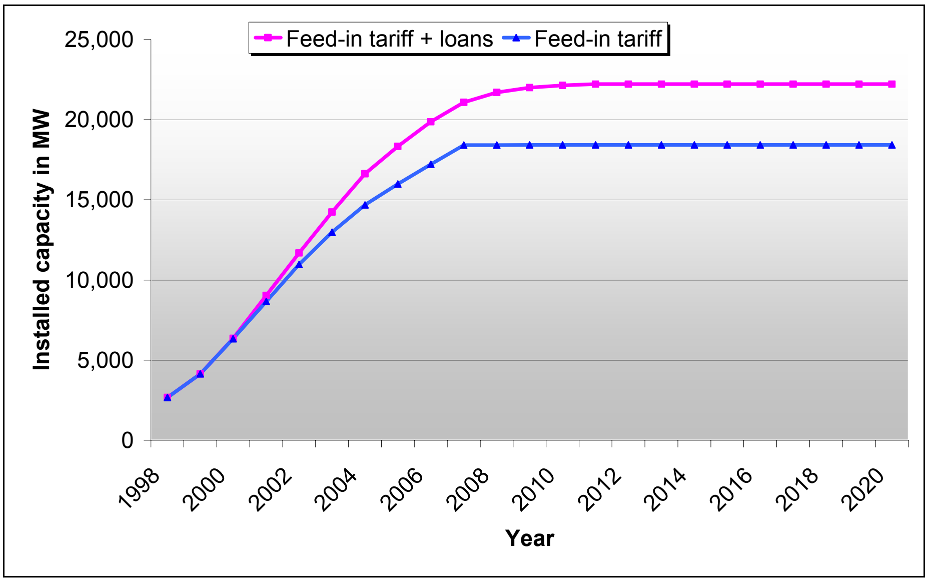


Figure 7-8: Simulation results
Source: own illustration

The results of the simulation run show the considerable impact of the availability of soft loans on the simulated development of wind energy in Germany. After 2002 both simulation runs differ considerably in the development of the installed capacity. At the end of the simulation period the difference between the installed capacities reaches 3800 MW. These results underline the importance of the availability of these loans. In addition it has to be taken into account that the availability of low interest loans also helps to attract the additional private capital needed for the investments, an effect which is not yet covered in the simulation. These results might provide some insights into the design of the support of the beginning development of the offshore wind energy in Germany which struggles to take off. Since the offshore wind energy incorporates more technical risks, it could be valuable to provide additional support by soft loans in order to attract the necessary private capital.

7.3.5 Summary and outlook

This section presents a first version of an agent-based approach to the simulation of the expansion of renewable electricity generation in Germany (for more details see also (Sensfuß et al., 2006). Although the first version of the model is rather simple, it can successfully be calibrated to reproduce the development of wind energy in the period 1998-2005. The described case study on the future development of wind energy with different support conditions shows the considerable impact of the availability of low interest rate loans on the actual development. Future work could be directed to a better validation of parameters and a more detailed representation of investment decisions and the integration of different support schemes. But it has to be taken into account that a detailed agent-based simulation of player decisions requires extensive empirical data which may not be available in many cases. An additional task could be the extension of the simulation to a European level in order to get a better representation of technology learning. However, the first results presented in this study show that the selected approach seems to be promising in order to get new insights into the model-based analysis of support policies.

7.4 Appraisal

This chapter presents some additional modules developed for the PowerACE Cluster System. The developed modules cover very different topics, such as the market for private consumption, load management and the simulation of investment processes for renewable electricity generation. Although the developed modules are characterized by a strong simplification of the real world situation and a lack of empirical data, they can provide some interesting insights with regard to the analysed topics. The developed modules underline the flexibility of the modelling approach selected in this thesis. The procedure to develop a model which combines the bottom-up modelling architecture of agent-based simulation with a detailed and extensive data set on the German electricity sector offers a number of possibilities to build additional modules for the analysis of research topics related to the electricity sector. In addition the developed modules show interesting perspectives for the future model extensions. It may be a valuable effort to extend some of the modules, which have been designed for demonstration purposes and small case studies, with regard to their complexity and scope.

8 Summary, conclusions and outlook

8.1 Motivation

The background of the analysis carried out in this thesis is the growing importance of renewable energy sources in the electricity sector in Germany. The future targets for renewable electricity generation in Germany and the European Union indicate that this growth is likely to continue. The increasing electricity generation from renewable energy sources is the result of a continuous support policy for these sources which is mainly based on a feed-in tariff. The framework conditions of the German support scheme have changed considerably since it was first established. Major developments include the liberalization of the electricity markets and the introduction of the European emissions trading system. Under the given framework conditions, supporting electricity generation from renewable energy sources has a number of impacts on players in the electricity sector. One aspect which gains the most public attention is the fluctuating nature of electricity generation based on wind energy and photovoltaic systems. Other aspects, in contrast, are rarely discussed such as interactions with the electricity market and the CO_2 market.

8.2 Objective

The central goal of this thesis is to provide a comprehensive analysis of the major impacts on the German electricity sector of the German support scheme for renewable electricity generation. Promoting renewable electricity generation has a number of effects on the electricity sector, e. g. the effect on prices on the electricity market and the CO_2 market and other effects related to balancing and managing the system. Due to the number of effects, it seems important to be able to quantify the effects of renewable electricity generation in monetary terms. Such a quantification can help to provide important background information for the current discussion on the support for renewable electricity generation.

This task poses new challenges with regard to the level of detail required and the complex framework conditions in a liberalized electricity market. Modelling approaches which are commonly used in the electricity sector such as optimisation models are not well suited for the given task since they lack the flexibility and the capability to integrate the perspective of single players. In order to deal with these challenges, a simulation platform is developed based on the concept of agent-based simulation. Thereby the level of detail applied and its consequences leads to new challenges concerning data management and computational resources. Therefore the model development itself becomes a further objective of this thesis.

8.3 Procedure

In a first step, important developments in the German electricity sector are analysed in order to provide the background for the further analysis. The most important developments are market liberalization, the introduction of the European emissions trading system, the support for renewable electricity generation and the support for combined heat and power plants.

Criteria for the required analysis tool are then developed against this background. Due to the fluctuating nature of some renewable electricity generation, a high level of technical detail is required for a reliable analysis. Since the electricity sector is characterized by the interaction of several markets, the model has to be able to deal with multiple markets. The goal of analysing the impacts on different players in the liberalized electricity markets requires the players' perspective to be integrated. Another conclusion which can be drawn from analysing recent developments is that the model has to be flexible in order to adapt to rapidly changing framework conditions.

The available modelling approaches are analysed using these criteria. Comparing the analysed modelling approaches reveals that agent-based simulation is the most promising approach for the given task.

In the next step, the available literature on agent-based simulation is analysed. The analysis shows that considerable progress has been made in the development of different simulation models in recent years, although the approach is still relatively new. The developed models have evolved from rather simple models with an aggregated representation of electricity supply and demand to large-scale simulation platforms which are capable of dealing with multiple markets and time scales. Major challenges are designing adequate agent architecture and selecting suitable learning algorithms. But the most important challenge for the developed models is the validation of the model results. In the given context, providing adequate data for the simulation becomes an important task, especially if it is taken into account that not all data is available to the public. Since no model is publicly available which fulfils the requirements of the central goal to analyse the impact of renewable electricity generation an own simulation platform is developed.

The developed model utilizes the bottom-up modelling philosophy of the concept of agent-based simulation. Special emphasis is placed on a detailed representation of the fundamental market structure and market data. These include electricity demand, renewable electricity generation and a detailed data set of the German power plant portfolio. The high degree of detail and the use of random variables make additional demands on data and model management. In order to deal with these challenges, the PowerACE Cluster Management System is developed which makes it possible to employ the computing power of several computers and provides automated tools for the analysis of the model results. Another important step is the calibration of the model to the market prices on the German spot market for electricity.

After the calibration procedure, the developed model is used to analyse the major effects of renewable electricity generation on the German electricity sector. These include the effects on the market prices of the electricity market and the CO_2 market, the costs related to the balancing and management of the system and the impacts on conventional electricity generation.

Three additional case studies are carried out to demonstrate the flexibility of the developed model. These case studies deal with the analysis of pricing developments on the electricity market for private consumption, the assessment of the potential income from load management on the electricity markets and the simulation of the expansion of renewable electricity generation capacity.

8.4 Results

The developed model is used to support the analysis of the impact of the German support scheme for renewable electricity generation on the German electricity sector in the year 2006. The benchmark and calibration procedure shows that the developed model is capable to reproduce price developments on the German spot market. The Pearson correlation of the simulated time series and spot market prices is considerably higher than the correlation of spot market prices in different years. Another interesting outcome of the calibration procedure is the integration of CO_2 prices into spot market prices. While the results indicate that CO_2 prices for gas and hard coal are integrated to 100 % into the bid price in the year 2006, it is interesting to note that in case of lignite power plants simulation results indicate that only 20 % of the CO_2 price are integrated into the bid price. This aspect could affect emission reduction strategies as lignite fired plants are characterized by the highest CO_2 emissions.

The analysis of the impact of renewable electricity generaton on the electricity sector shows that the interaction of the supported electricity generation with the electricity market and the CO_2 market creates effects with a monetary volume of several billion Euro. These effects are illustrated in Figure 8-1.

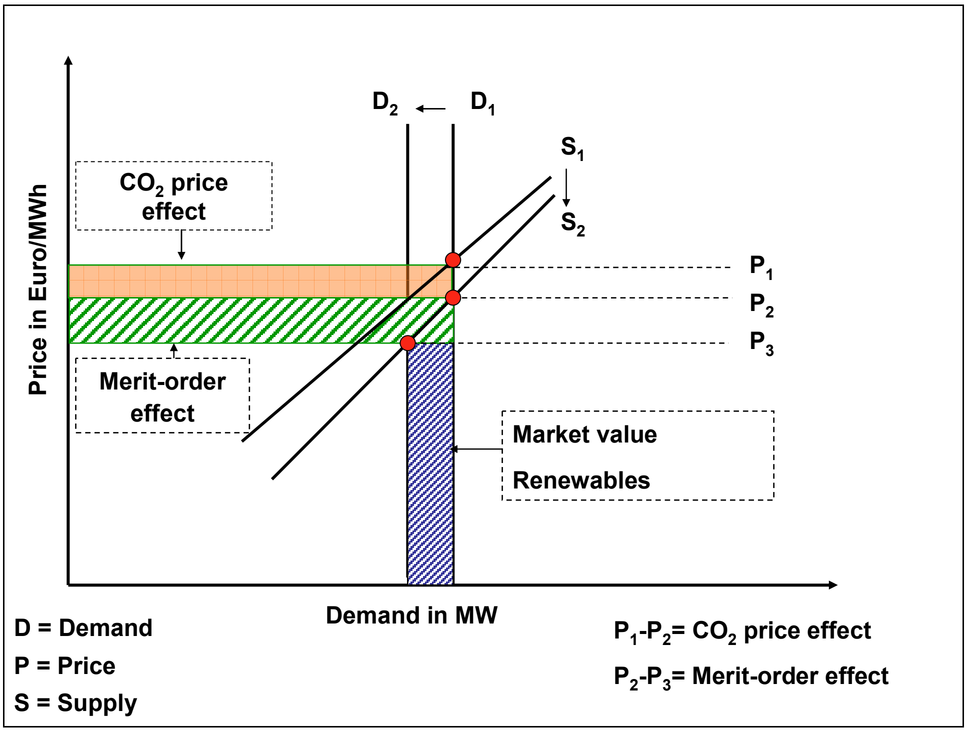


Figure 8-1: Illustration of the major effects of renewable electricity generation on the spot market for electricity

Source: own illustration

One important effect is the merit-order effect. The supported renewable electricity generation reduces the electricity demand that has to be met by conventional power plants. In a competitive electricity market this effect leads to a reduction of market prices. The calculated monetary volume of this effect amounts to 5 billion Euro in 2006 assuming that the spot market is the leading indicator for all electricity trade. This can lead to savings for suppliers and their consumers. The considerable volume of the effect can be explained by the shape of the supply curve which has the highest slope in times of peak demand. Peak power plants are characterized by high variable generation cost. Since the most expensive power plants are the first to be replaced by renewable electricity generation, even small amounts of renewable electricity generation can have a considerable impact on electricity market prices. Due to the fluactuating character of renewable electricity generation the impact on market prices varies heavily on an hourly timescale. A similar effect is caused by the interaction of renewable electricity generation with the CO_2 market. The renewable electricity replaces electricity generated by mainly fossil-fired power plants thus reducing the overall CO_2 emissions of the electricity sector. An analysis of alternative saving options shows that a minimum CO_2 price of 20 Euro/t is required in order to save the same quantity of CO_2 using other means. Thereby it is assumed that only half of the CO_2 savings can be achieved by flexible mechanisms such as the Clean Development Mechanism [CDM] and Joint Implementation [JI]. The remaining CO_2 savings are made within the European industry and electricity sector. If it is assumed that the CO_2 price of 20 Euro/t were the CO_2 price without supported renewable electricity generation, the impact of this price effect can be calculated. As the CO_2 price is part of the variable cost of power plants, the market prices on the spot market would be higher without renewable electricity generation. The monetary volume of this effect is estimated at 1.38 billion Euro. Besides the monetary volume the calculated volume of the CO_2 savings of 38.5 Mt for the year 2006 and the cost of alternative saving options in Germany underline the important contribution of renewable electricity generation to the reduction of green house gas emissions in Germany.

It should be stated that these effects are rarely discussed in the public and the scientific community. Especially the estimation of the CO_2 price effect is subject to considerable uncertainty. The monetary volume of these effects indicates that more attention should be given to their discussion and analysis. An open issue is the question of how these effects influence international electricity trade. Another aspect is the loss of profit for the generation companies caused by the reduction of market prices as a result of the merit-order effect and the CO_2 price effect. Based on the PowerACE Cluster System, the lost profits can be estimated at approx. 5.3 billion Euro in 2006, approx. 1.1 billion Euro lower than the sum of the merit-order effect and the CO_2 price effect.

Other important aspects are the market value of renewable electricity generation and the value of the CO_2 savings. If the market prices of 2006 are applied, these values can be estimated at approx. 2.5 billion Euro and 0.7 billion Euro, respectively.

A third category of effects are the costs connected with the management and the balancing of the system. The required balancing reserve and the intra-day profile service were estimated to reach 253 and 215 million Euro, respectively. Minor effects include grid extension and the costs due to partial load operation of conventional power plants which equalled 52 and 38 million Euro, respectively. An overview of the discussed effects is given in Table 8-1.

Another important part of the analysis is the players' perspective. An overview of the possible net effects is given in Table 8-2. If effects like the merit-order effect and the CO_2 price effect are taken into account, the support scheme for renewable electricity generation does not necessarily result in higher costs for the demand side represented by suppliers and consumers. The price reductions outweigh the net support payments and the cost of balancing the system by about 3 billion Euro in 2006. These results contradict the commonly held opinion that supporting renewable electricity generation leads to additional costs for consumers (see also Bundesministerium für Wirtschaft und Technologie [BMWI] and Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2006a). On the other hand, generation companies are likely to lose profits to a magnitude of 5 billion Euro as a result of the reduced market prices in 2006. In the given context it has to be stated that the resulting long-term effects on market structure and market efficieny are not analysed in this study.

Table 8-1: Overview of the major impacts of renewable generation on the electricity sector for the year 2006

Effect	**Volume** Million €	**Uncertainty**	**Appraisal of the estimation**
Support payments	5,380	Low	–
Lost profit generators	5,260	High	medium
Merit-order effect	4,980	High	medium
Value of RES-E generation	2,540	Low	–
CO_2 price effect	1,380	Very high	low end estimation
Value CO_2 savings	655	Very high	medium
Cost reserve capacity & energy	253	Medium	high end estimation
Profile service intra-day	215	Medium	medium
Grid extension	52	Low	high end estimation
Operation of power plants	38	Medium	high end estimation

The developed modelling approach allows these effects to be analysed on an unprecedented level of detail. Despite this and the considerable effort invested in the analysis, it has to be stated that the estimation of the discussed effects is still subject to considerable uncertainty which is highest for the CO_2 price effect due to the necessity of various assumptions. In addition it has to be taken into account that the price reduction is not likely to stop at the German border. As the national electricity markets are connected by transmission lines with limited capacity, it is likely that supported electricity generation in Germany also affects market prices in neighbouring countries. It is also possible that the price reductions may be even higher if good wind conditions in northern Europe lead to a large reduction in the remaining system load to be covered by conventional power plants in many national markets. Another issue is that the merit-order effect and the CO_2 price effect are very sensitive to the underlying fuel price, especially the gas price, which is an important factor for the price of peak load power plants.

Table 8-2: Possible net effect of the discussed effects on different players

Category effect	Generation companies volume	Renewable generators volume	Supplier ⇔ Consumer volume
	Million € 2006		
Lost profit generators	-5,260		
Support payments		5,380	-5,380
Merit-order effect			4,980
Value RES-E generation			2,540
CO_2 price effect			1,380
Value CO_2 savings	655		
Cost system reserve*	253		-253
Profile service intra day*	215		-215
Grid extension			-52
Operation of power plants	-38		
Possible total net effect	**-4,643**	**5,380**	**3,000**

* These effects represent additional turn over not profits, therfore excluded from the sum
Legend: (-) negative effect (losses) (+) positive effect

In the last chapter, special emphasis is given to demonstrating the potential of the developed modelling approach. Three special modules of the developed simulation platform are applied in different case studies. The first case study analyses the development of market prices on the retail market for private consumption. Based on the developed module, it can be shown that rising prices on the retail market can evolve without the tacit collusion of market players if the market awareness and participation of consumers remain at the low level currently observed. In another case study the developed algorithm for the utilization of pump storage plants is used to assess the potential income of load management options. The results indicate that the potential income on the reserve markets is higher than the income that can be generated on the spot market under the current market conditions. Another interesting result is that the potential income that can be generated by managing the load of most applications in the household sector is between 0.4 Euro per year and about 3 Euro per unit and year. This result shows that, under the given market conditions, the costs for the communication infrastructure and the management of the load pools have to be very low in the household sector in order to be feasible. The last case study develops a new agent-based approach to the simulation of investments in renewable generation capacity. The developed module is applied to show the importance of soft loans with reduced interest rates for the expansion of wind energy in Germany.

8.5 Evaluation, conclusions and outlook

This thesis has two major objectives. The first is to analyse the effects of renewable electricity generation on the electricity sector. As a result of the requirements of this task an agent-based simulation platform is developed. Since the developed simulation platform utilizes a new modelling approach, the model development itself is a secondary objective of this thesis. In order to reflect the fact that these two objectives are totally different in character, this section is divided into two parts: one deals with the results of the analysis regarding supported renewable electricity generation and the other with the methodological development.

8.5.1 Conclusions and outlook concerning the analysis of the effects of renewable electricity generation

The results of the main case study on the impacts of renewable electricity generation on the electricity sector show that the major effects in monetary terms stem from the interaction with the electricity markets.

The considerable volume of the effects presented above is in sharp contrast to their prominence in the public debate on the German support system, which is heavily dominated by the costs related to balancing the fluctuating renewable electricity generation. As the discussed effects on market prices outweigh the financial volume of all balancing related costs more than ten times, more research should be done on these aspects, especially the analysis of the international perspective.

Another important issue is the analysis of the impacts on the different players. Does the competitive situation on the market for consumers force suppliers to pass on the discussed savings? The analysis of the electricity market for private consumption in Chapter 7 indicates that this does not necessarily happen because of the low market awareness and participation of private consumers. Furthermore, the lost profits of generation companies should also be subject to further analysis. Do the reduced profits endanger the capability of the generation companies to build new plants and replace old ones? In the current situation of high profits of the generation companies and various announced construction projects (Bundesministerium für Wirtschaft und Technologie [BMWI] and Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2006a) this may not be the case, but is this situation likely to change with a greater volume of renewable electricity generation? Does the additional generation capacity increase the competition on the market or do the big utilities which represent a considerable share of the generation capacity and the electricity demand manage to keep peak prices on a high level? Considering the financial volume of the discussed effects, it seems obvious that further research is needed to answer these questions. Thereby the concept of agent-based simulation of the electricity sector can be a valuable tool.

8.5.2 Methodological evaluation and outlook

The developed model combines the bottom-up modelling architecture of agent-based simulation with a detailed and extensive data set on the German electricity sector. The developed agent-based simulation platform can successfully be applied to the analysis of the electricity sector. The centre of the model is the simulation of the spot market for electricity. This simulation incorporates important aspects such as the player orientated modelling approach and the integration of multiple markets such as the spot market and the reserve markets. For these markets, each player decides independently on the volumes and the corresponding prices bidden. In this way the developed model deviates from the optimization approach commonly applied in the electricity sector. In many cases these models are designed to compute a cost optimal solution for the entire system. New approaches are now needed because the liberalized electricity sector is no longer characterized by centralized planning but by the complex, market-orientated interaction of different players. In combination with detailed simulation on an hourly timescale, the developed model allows a more realistic representation of the real world electricity markets.

In the analysis of the merit-order effect and the CO_2 price effect additional player strategies and learning algorithms were not applied in order to keep the model manageable. However, in the case study on the electricity market for private consumption, a reinforcement learning algorithm which is commonly applied in agent-based simulation is successfully integrated into the simulation platform. The flexibility of the selected modelling approach is underlined by the additional case studies carried out in Chapter 7. Although the additional modules developed are limited in their complexity, they do provide some interesting insights with regard to the analysed topics. In combination with the developed tools and cluster management, the developed simulation platform provides a good basis for future developments and extensions.

The extension of the developed simulation to a European scale comprises one such development. This could provide important insights into the international perspective of the discussed effects of supported renewable electricity generation. Such a model could be very valuable especially if the current debate on harmonizing renewable support schemes is taken into account. But it must be considered that such an undertaking places enormous demands on the underlying data set and the computational resources. Other interesting extensions to the simulation of the German wholesale market for electricity could be the dynamic simulation of heat demand in order to better integrate combined heat and power plants and the dynamic simulation of power plants in partial load mode. These developments could contribute to further increase the realism of the developed model. This discussion shows that the selected approach provides a good basis for future research which is clearly needed to better understand the developments in the electricity sector at national and European level.

Appendix

Table A-1: Examples of CGE models

Abbreviation	Complete name	Additional information
NEWAGE	National, European, World-wide Applied General, Equilibrium modelling system	University of Stuttgart http:/www.ier.unistutgart.de/forschung/projektwebsites/forum/index/a_index.htm
LEAN	LEAN	University of Oldenburg http:/www.ier.unistugart.de/forschung/projektwebsites/forum/index/a_index.htm
GEM-E3	General equilibrium model for energy-economy environment interactions	National Technical University of Athens Catholic University of Leuven Centre for European Economic Research http://www.gem-e3.zew.de
GTAP	Global Trade Analysis Project	Purdue University http://www.gtap.agecon.purdue.edu/models/current.asp
WIAGEM	World Integrated Assessment General Equilibrium Model	German Institute for Economic Research http:/www.ier.unistutgart.de/forschung/projektwebsites/forum/index/a_index.htm
GREEN	General Equilibrium Environmental Model	Organisation for Economic Cooperation and Development http://www.oecd.org/dataoecd/25/8/1919148.pdf
GTEM	Global trade and environment model	Australian Bureau of Agricultural and Ressource Economics [ABARE] http://www.abareconomics.com/research/models/GTEM/GTEM.htm
DART	Dynamic Applied Regional Trade	Kiel Institute for World Economics http://www.unikiel.de/ifw/forschung/dart/dart_e.htm
PACE	Policy analysis based on computable equilibrium	Centre for European Economic Research http:/www.ier.unistutgart.de/forschung/projektwebsites/forum/index/a_index.htm

Table A-2: Examples of macroeconometric models

Abbreviation	Complete name	Additional information
E3ME	Energy-Environment Economy Model of Europe	Consortium led by Cambridge Econometrics http://www.camecon.co.uk/e3me/intro.htm
LIFT	Long-Term Interindustry Forecasting Tool	Interindustry Forecasting University of Maryland http://www.inforumweb.umd.edu/Lift.html
INFORGE	Interindustry Forecasting Germany	German economy GWS mbH, Osnabrück http://www.gws-os.de
PHANTA RHEI	PHANTA RHEI ("Everthing flows")	German economy GWS mbH, Osnabrück http://www.gws-os.de

Table A-3: List of pump storage plants

Plant	Volume MWh	Capacity MW	Income Ratio* %
Einsiedel	23	1.2	98.90
Glems	560	90	112.10
Wehr	5000	977	111.24
Otilienberg	200	38	111.35
Happburg	840	160	111.34
Rabenleite	630	130	111.05
Waldeck1	478	140	110.13
Waldeck2	3428	440	113.16
Erzhausen	940	220	110.64
Koepfchen-Werk	580	150	110.43
Rönkhuasen	700	140	111.17
Markersbach	4,018	1135	110.21
Niederwartha	591	131	110.79
Wendefurth	523	95.2	111.50
Geesthacht	600	140	110.65
Hohenwarte2	2087	397	111.33
Häusern	46,330	119.44	75.49
Säckingen	2064	369.16	111.55
Schwarzenbachwerk	10,550	43	76.16
Waldshut	40,237	159.36	76.13
Witznau	62,684	219.37	75.94
Eibele	2	0.64	–
Höllbachkraftwerk 3	287	1.38	75.78
Leitzachwerk 1	550	50	110.64
Leitzachwerk 2	550	45	110.64
Warmatsgrund	20	4.6	111.51
Sorpetalsperre	7,120	7.3	75.26
Dhronkraftwerk	29	6	111.40
Bleiloch	8,817	99.6	77.95
Hohenwarte 1	6,108	69	77.95
Wisenta	54	1.28	78.91
Goldisthal	8,480	1,060	112.89

* Determined according to Chapter 5.5, Formula 5-13

Source: Based on :Verband der Elektrizitätswirtschaft [VDEW], 2000

Table A-4: Sectoral structure of electricity demand

Sector Industry		**Sector Services**	
Branch	**Technology**	**Branch**	**Technology**
Mining	Others	Banks, insurances	Others
Chemicals	Others	Construction	Others
Food	Others	Government	Others
Food	Process heat	Trade	Lighting
Food	Others	Trade	Cooling
Automotive	Power	Trade	Others
Automotive	Others	Handcraft	Others
Glas&Ceramics	Others	Hotels and Restaurants	Others
Basic Chemicals	Chlorine	Hospitals	Others
Basic Chemicals	Power	Agriculture	Others
Basic Chemicals	Others	Schools, public buildings	Others
Plastics	Others	Heating	Storate Heating
Engineering	Power	Heating	Heating
Engineering	Others	Others	Street Lighting
Metal working	Others	Others	Others
Metals	Electric steel		
Metals	Rolled steel		
Metals	Others		
Non ferrous metals	Alumimium		
Non ferrous metals	Others		
Paper	Power		
Paper	Others		
Refineries	Others		
Others	miscellaneous		
Others	Others		
Cement & Earthenware	Cement		
Cement & Earthenware	Others		
Sector Households		**Sector Transport**	
Branch	**Technology**	**Branch**	**Technology**
Households	Audio	Transport	Rail
Households	Lighting	Transport	Public transport
Households	TV	Transport	Local services
Households	Cooking		
Households	Cooling		
Households	Storage heater		
Households	Heating		
Households	Others		
Households	Dish washer		
Households	Dryer		
Households	Hot water		
Households	Washing Machine		

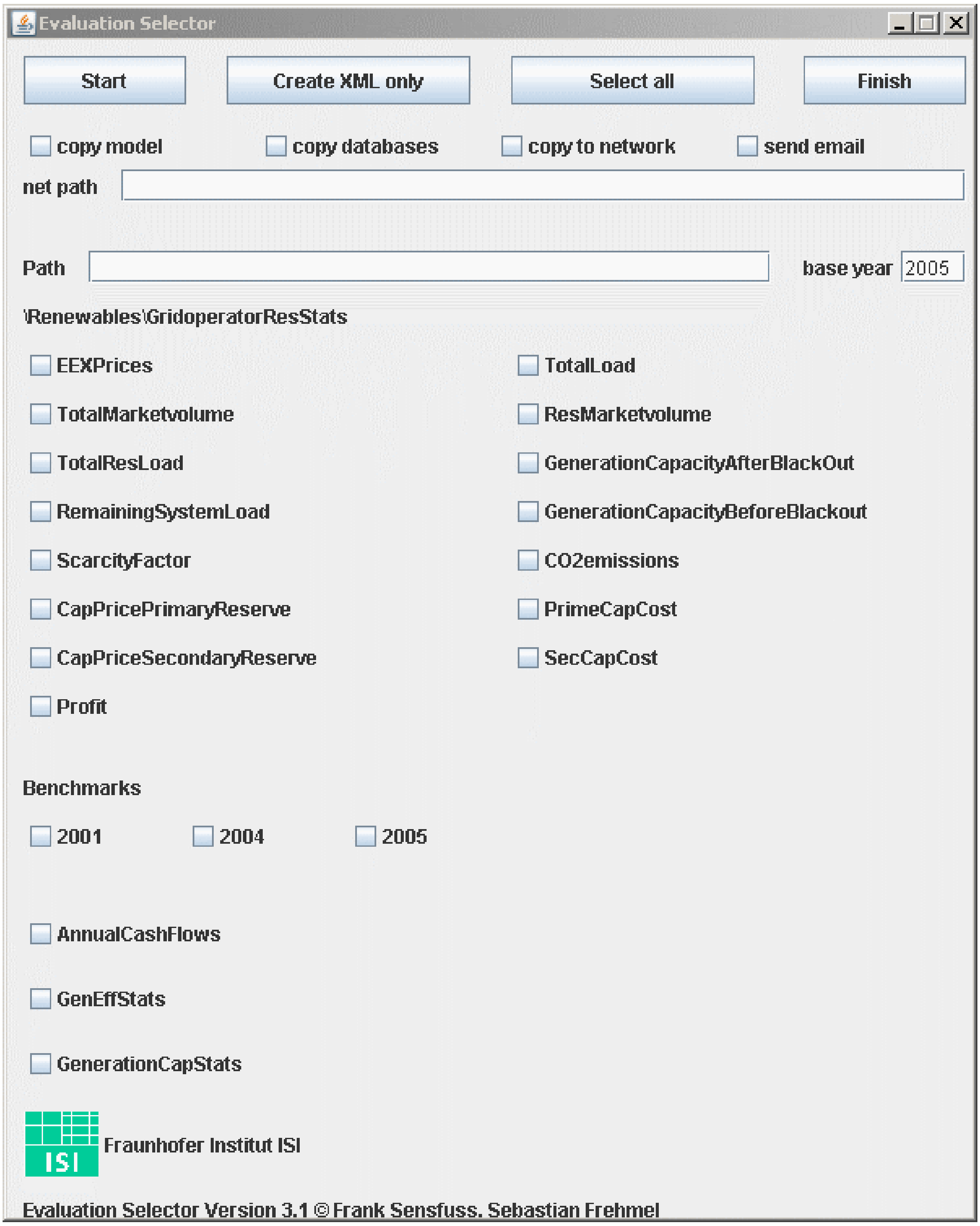


Figure A-1: Graphical user interface of the PowerACE Analyzer

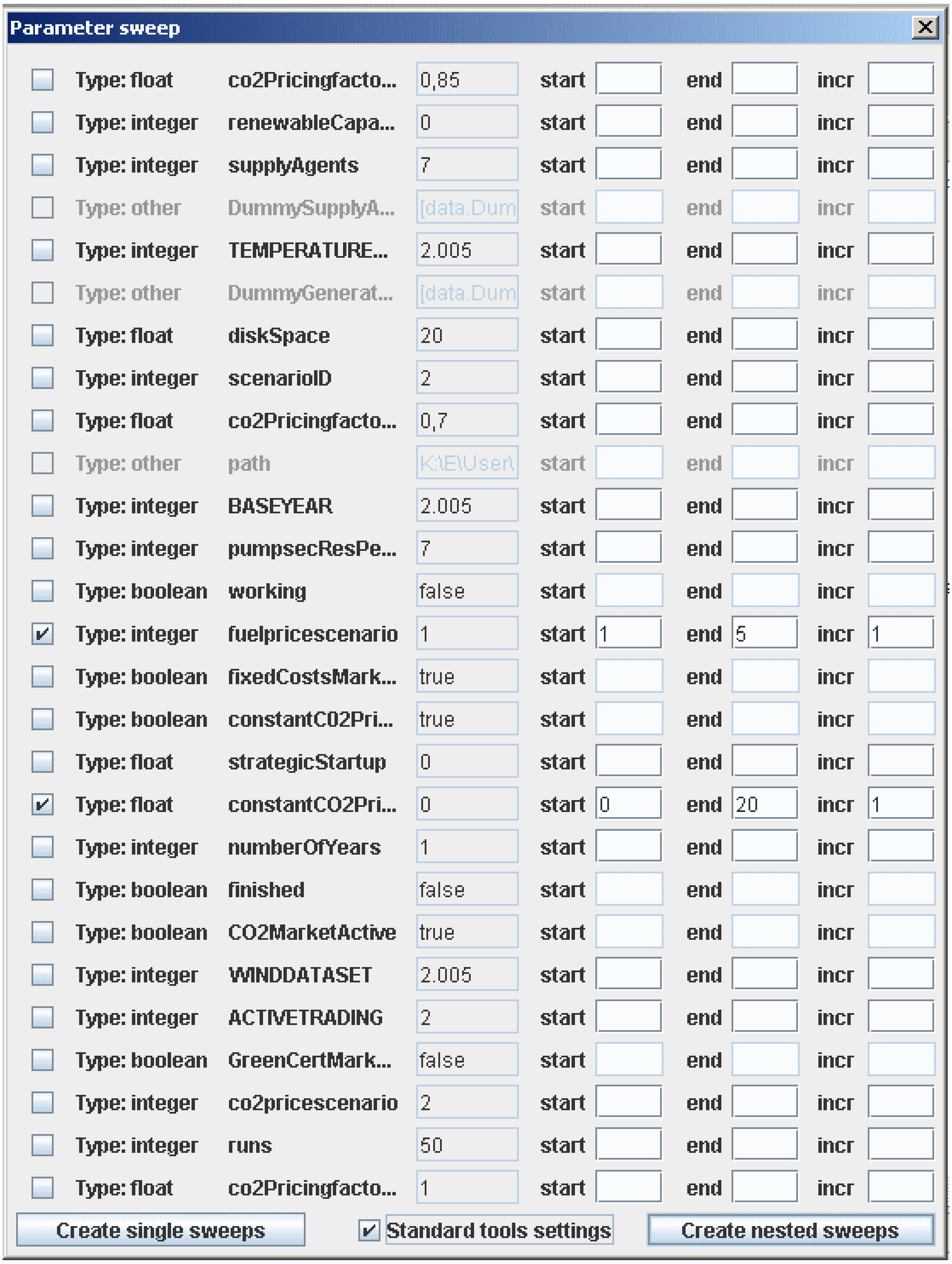


Figure A-2: Graphical user interface of the Scenario Creator

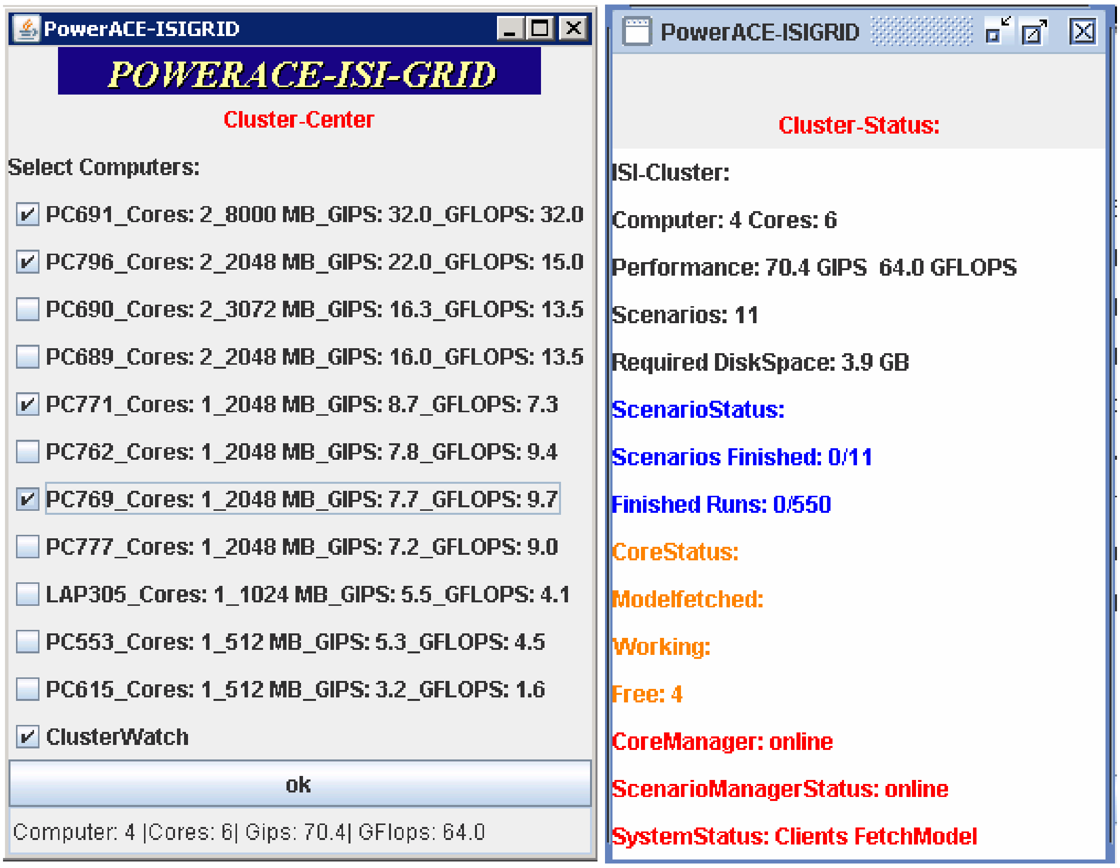


Figure A-3: Graphical user interface of the Cluster Management

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