Modelling the future development of renewable energy technologies in the European electricity sector using agent-based simulation

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Abstract

Increasing the share of renewable energy sources (RES) in final energy consumption forms an important part of the EU's energy and climate strategy due to the potential contribution of RES to climate protection and security of supply and to the economic competitiveness of the energy system. Several factors substantially influence the future prospects for the use of renewable energy technologies (RET); these include the combination of regionally heterogeneous resource availability and electricity generation costs, referred to as cost-resource curves. Most of the existing RET are not yet economically competitive with conventional conversion technologies. To try and make renewable energy technologies (RET) economically viable for investors, various policy support schemes, such as feed-in tariffs or quota obligations, have been applied for over a decade. This raises the questions how the use of RES will develop in the future under different policy regimes and what the involved economic implications are.

A quantitative modelling tool is developed in this thesis to assess the potential long-term contribution of RET in the European power sector. Since the future market development of RET is judged to depend in particular on individual investors' decisions, an agent-based simulation (ABS) approach is chosen. ABS is an approach which analyses global complexities based on interactions on the micro-level. This thesis pursues a novel approach to assessing RET diffusion processes and policies from an agent-based perspective based on spatially explicit cost-resource curves. The cost-resource curves derived in this analysis are adapted to the requirements of a multi-agent model. Owing to the detailed techno-economic characterisation of RET and the potential to depict various policy options, the developed simulation model could help to design policies suited to the relevant agents in the renewable energy sector, or point out existing investment opportunities for interested stakeholders. With regard to the recently suggested policy option of statistically transferring final energy to other countries for target accounting, special attention is paid to the question of at which price the final energy can be statistically exchanged.

According to the scenario analysis performed with the developed simulation model, the strong future market development of RET appears to be feasible provided that adequate support instruments are applied. Depending on the degree of political ambition and the type of policy instrument applied, electricity generation from RET is expected to reach between 1.4 and 2.0 PWh by 2050. This development involves total investments ranging from 791 billion euro to 1,273 billion euro in the period from 2005 to 2050. In particular, onshore wind power plants are expected to experience considerable growth as a result of their significant resource potential and low electricity generation costs compared to other RET alternatives. Comparing the results of modelling different support mechanism reveals that the additional renewable power plant capacity being built fluctuates more strongly when quota obligations are applied. This is essentially due to the high sensitivity of the certificate prices to quota targets. Another conclusion drawn by this study is that technology-specific policy support tends to imply lower policy costs than technology-neutral support.

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List of Abbreviations

ABG .... Agricultural biogas
ABS...................... Agent-based simulation
ACE .... Agent-based computational economics
AP .... Agricultural products
AR........................ Agricultural residues
ARMA .... Auto-Regressive Moving Average
BIGCC .... Biomass integrated combined cycle
BL .... Black liquor
BOS...................... Balance of system
BW .... Biowaste
CAPM .... Capital asset pricing model
CDM .... Clean development mechanism
CHP...................... Combined heat and power
CO_2....................... Carbon dioxide
COP...................... Conference of the Parties
CSP .... Concentrating solar power
csv .... Comma-separated values
EC .... European Commission
EEA...................... European Environment Agency
EGS .... Enhanced geothermal systems
ENTSO................. European Network for Transmission System Operators
EP......................... Economic Potential
ETS .... European trading scheme
EU .... European Union
EU12 .... All Member States of the European Union which have joined the Union in 2004 and 2007 including Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Malta, Latvia, Lithuania, Poland, Romania, Slovakia and Slovenia
EU15 .... All Member States of the European Union which have joined the Union before the enlargement of 2004 including Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden and the United Kingdom
EU27 .... All Member States of the European Union as of January 2007
FIT .... Feed-in tariff
FLH...................... Full-load hours
FP .... Forestry products
FR......................... Forestry residues
GDP .... Gross domestic product
GHG..................... Greenhouse gases
GIS .... Geographical information system
HMS..................... Hybrid modelling system
IDE....................... Integrated development environment
IEA....................... International Energy Agency

IPCC..................... International Panel of Climate Change
IR .... Interest rate
kWh...................... Kilowatt hours
LG .... Landfill gas
MAUT .... Multi-Attribute Utility Theory
MS........................ Member States
MWh .... Megawatt hours
NAP .... National allocation plan
NPV .... Net present value
NREAP .... National renewable energy action plan
OECD................... Organisation for Economic Co-operation and Development
OOP .... Object-oriented programming
ORC .... Organic Rankine Cycle
OTEC .... Ocean thermal energy conversion
OWC .... Oscillating water columns
ppm .... parts per million
PR......................... Performance ratio
PV .... Photovoltaics
PVGIS .... Photovoltaic Geographic Information System
R&D..................... Research and development
RES .... Renewable energy sources
RES-E .... Electricity generation from renewable energy sources
RET .... Renewable energy technologies
RIGES .... Renewables-intensive global energy scenario
RP......................... Realisable potential
RPP .... Renewable power plant
SD .... System dynamics
SET-Plan .... Strategic Energy Technology Plan
SG .... Sewage gas (sludge)
SRES .... Special Report on Emission Scenarios
STC .... Standard test conditions
TGC .... Tradable green certificate
TP......................... Technical potential
TWh .... Terawatt hours
UN........................ United Nations
UNFCC .... United Nations Framework Convention on Climate Change
WACC .... Working average costs of capital
XML..................... Extensible markup language

1 Introduction

1.1 Background

The dominant role of fossil fuel-based energy conversion in the European energy system means that new challenges have been emerging for policy makers. Rising concerns about the depletion of resources, a greater dependency on imports and the key role of fossil fuel combustion in climate change have sparked a debate on transforming the European energy sector to a secure and competitive low carbon system. The European Union (EU) has put in place a common energy policy strategy to achieve the required transition (European Commission 2006). In this context, the European Commission (EC) has committed itself to reducing greenhouse gas (GHG) emissions to 20 % below 1990 levels by 2020 (European Commission 2008a).

The development and diffusion of renewable energy conversion technologies (RET) are of key importance for the shift to a secure and competitive low carbon energy system. In contrast to fossil fuel-based energy conversion technologies, RET utilise energy flows from natural phenomena such as solar irradiation or geothermal energy, which are naturally replenished after extraction or are inexhaustible from a human perspective. Due to the low level of GHG emissions associated with RET, substituting fossil fuel-based conversion technologies with RET can contribute substantially to climate change mitigation. In addition, the indigenous availability of renewable energy sources (RES) helps to decrease the import dependency of the European energy sector. That is why the EC, along with the GHG reduction target, also set itself the objective of increasing the share of RES in final energy consumption to 20 % by 2020.

Whilst the characteristics of RET make them suitable to tackle the problems of climate change and resource scarcity caused by fossil fuel-based energy conversion, their use also involves certain challenges. One of these is related to the potential availability of RES. Even though the maximum availability of primary resources in terms of the physical energy supply is not the crucial obstacle to the diffusion of RET, several other factors limit the realistically exploitable potential of RES. Several restrictions limit the theoretical availability of RES including geographical aspects such as the land available for the construction of renewable power plants and technical aspects, mainly to do with the conversion efficiencies of technology options. The resulting technical renewable energy potential is characterised by a heterogeneous spatial distribution across Europe, meaning that some countries or regions are better off than others. However, the differing national potential availability of RES was not considered when the EU-wide objective was translated into national targets.

Most of the existing RET are not yet economically competitive with conventional conversion technologies. Thus, the market development of RET is currently being stimulated by various support schemes at national level. The most frequently used promotion schemes in the electricity sector are price-based feed-in tariff (FIT) systems and quantity-driven quota obligations. The latter tend to be applied in combination with a green certificate trading system. As a result of existing policy support on European and national levels, the renewable energy sector in the EU has undergone a dynamic development in recent years, especially in the electricity sector. The EU's electricity generation from RET rose from 312 TWh in 1990 to

558 TWh in 2008 (EurObserv'ER 2009, p. 94; Eurostat 2010). Whilst hydropower plants, which have been used for many years, have experienced only moderate growth since the late 1990s, electricity generation from emerging RET increased more than sixfold from 37 TWh in 1997 to 225 TWh in 2008 (EurObserv'ER 2009, p. 92; Eurostat 2010).

With increasing market penetration, the applied RET have developed dynamically in particular in terms of decreasing electricity generation costs. This requires continuous adaptation of the political framework conditions. Since the implementation of policy instruments at national level does not necessarily lead to the most cost-effective development of RET, the EC introduced new mechanisms in its most recent legislative update, the Directive 2009/28/EC, allowing Member States (MS) to cooperate on RET support and target compliance using flexibility mechanisms such as statistical transfers. These allow countries which have more renewable final energy than needed to meet their national target to virtually transfer the renewable final energy to countries struggling to comply with their renewable targets.

Besides the described technical, political and economic framework conditions, additional patterns of technology diffusion processes may exert considerable influence on the market development of RET. Thus, a failure of the markets in terms of incumbent market participants exercising market power or insufficient knowledge networks may prevent or retard the adoption and diffusion of new technologies in the real world (Jacobsson & Johnson 2000, p. 631). In this context, Dawid (2006, p. 1255) emphasises the role of heterogeneous agent behaviour for processes of technology adoption and diffusion in general. In a similar way Dinica (2006) argues that the actors who realise investments are crucial for the diffusion of RET in particular.

In this context, the questions arise how the use of RET might develop in the future under different policy regimes and what the involved costs are. With regard to the recently suggested policy option of statistical transfers, special attention is paid to the question of the price at which the final energy can be statistically exchanged.

1.2 Objective and approach

The first main objective of this thesis is to investigate the potential long-term contribution of RET to European electricity supply. Taking into account the detailed technological capabilities and limits of RET the question emerges as to which technologies evolve to what extent under different framework conditions. The high complexity of RET diffusion processes and the intention to quantify the core economic and technological effects suggests the application of a quantitative assessment tool. However, the existing modelling approaches used to analyse this problem fall short when considering heterogeneous agent behaviour and the heterogeneous spatial distribution of the RES potential in an integrated way. Accordingly, the development of an appropriate modelling approach is the second main objective of this thesis.

The modelling approach to be developed has to meet certain requirements to adequately represent the diffusion of RET in the European power sector. These requirements are derived from the objective and the framework conditions that characterise the development of RET. Since the market development of RET strongly depends on the decentralised decision processes of investors pursuing different strategies (cf. Dinica 2006), the selected modelling approach has to consider the perspective of potential investors. This aspect combined with the requirement of integrating a dynamically evolving policy framework resulted in an agent-based simulation (ABS) approach being chosen. ABS analyses global complexities as the result of interactions on the micro level (cf. Ma & Nakamori 2005). Following a suggestion of Rosen (2008, p. 218), geographically explicit cost-resource curves are derived and integrated in the developed agent-based simulation model in order to take into account the techno-economic characteristics of RET and in particular the heterogeneous resource availability.

This thesis offers a novel approach to assessing the diffusion processes of RET from an agent-based perspective in combination with spatially explicit cost-resource curves which are adapted to the requirements of a multi-agent model. In addition, the current policy framework is considered in the developed simulation model. The thesis is organised as follows.

To start with, chapter 2 surveys the framework conditions and policy developments on EU level which are relevant for the renewable energy sector. Special emphasis is placed on the policy instruments applied to support RET and on the market development of renewables in the EU.

The third chapter analyses the suitability of the available modelling approaches. To analyse the long-term diffusion of RET, an ABS approach is chosen, which integrates geographically explicit resource curves. Major developments of existing modelling approaches dealing with several aspects of RET in general and the phenomena of technology adoption and diffusion are presented to reflect the current status of scientific knowledge.

Chapter 4 provides an overview of the techno-economic characterisation of RET for electricity generation including a detailed assessment of the available resource potential and the associated electricity generation costs, referred to as cost-resource curves. Owing to the considerable resource potential and the strong geographical dependence of electricity generation costs, cost-resource curves for onshore wind and solar photovoltaic power plants are derived in a detailed analysis which takes regionally explicit aspects into account. A geographical information system (GIS) is applied to process the spatially explicit data. Cost-resource curves for the remaining RET available for electricity generation are derived based on a review of the current literature.

Chapter 5 explains how the developed ABS model depicts the diffusion of RET in the electricity sector in terms of decentralised decision-making processes. This includes a description of the model architecture, the characteristics and conducts of the main agents as well as some details about the technical implementation. Furthermore, the chapter describes how the cost-resource curves derived within this thesis are adapted to the requirements of a multi-actor structure and integrated into the simulation model.

In chapter 6 the developed simulation model is applied to evaluate the future prospects of RET in the electricity sector under different policy regimes as well as the associated investment and costs. Special emphasis is placed on the issue of price indications for international trading mechanisms in terms of statistical transfers.

The thesis concludes with a critical reflection on the developed modelling approach and the obtained results, an outlook on future research and a summary in German.

2 Current situation and role of renewable energies in the EU

At present the European energy system is facing various challenges including climate change, increasing dependency on imports, decreasing availability of some fossil fuel resources and the affordability of the final energy provided. Therefore, energy policy, which was formerly mainly determined by national governments, has become increasingly important on the European policy agenda. The EU has put in place a common energy policy strategy in order to ensure a sustainable, secure and competitive energy supply. Due to the potential contribution of RES to mitigating climate change and to increasing security of supply, the stimulation of the market development of RES is part of the EU's energy strategy. The following sections show the development of energy policies on European level relevant for the renewable energy sector. Then, this chapter provides an overview of the current status and the historic development of RES in the EU. Finally, a short explanation of how climate change may affect the use of RES is given.

2.1 Policy developments in the European energy sector

Formerly, national energy policies in the MS lead to national energy mixes that partly differed considerably from each other, mainly in the electricity sector. To illustrate, France opted for an intensified use of nuclear power; the UK bases a large share of its electricity generation on gas, and Poland’s electricity generation is clearly carbon-dominated. The indigenous availability of energy carriers also has influenced the structure of electricity supply. That is, Austria, disposing of a considerable hydro power potential, makes preferential use of this domestic RES. As a result of several developments in the European energy sector, new challenges have been arising for policy makers in recent years. Increasing concerns about European security of energy supply, climate change patterns and the intention to increase the efficiency of energy supply required substantial changes in the political and legal framework conditions. This includes in particular the formulation of a common and coherent energy policy strategy on European level.

The EC initiated with a green paper, published in 2006, the development of a harmonised and integrated energy policy to face challenges of import dependency in combination with diminishing domestic energy sources, rising energy prices, global warming and a need for the replacement and reinforcement of the existing grid infrastructure. According to the green paper, the European energy policy should be mainly characterised by the following three characteristics (European Commission 2006):

- Competitiveness
- Sustainability
- Security of supply

Following the publication of the green paper, the EU intended to implement several legislative measures and rules in order to address each of the three main pillars of the long-term strategy. The liberalisation process of the European energy sector had even been initiated before the release of the green paper a decade ago in order to improve competitiveness (see section 2.1.1). Sustainability of the energy system is covered by climate change policies in a comprehensive way on the one hand (section 2.1.2) and by policies addressed at specific climate change mitigation options such as the use of RET on the other hand (see section 2.1.4). The security of a cost-effective and uninterrupted electricity supply has been dealt with in a distinct policy package (see 2.1.3).

2.1.1 Liberalisation of the European electricity sector

In order to replace the formerly monopolistic supply structure of European electricity markets, a process of liberalising European electricity markets was launched in the mid-nineties (Fichtner 2005, p. 39). The opening-up the formerly monopolistic European electricity markets to competition with the release of the directive on “common rules for the internal market in electricity” (The European Parliament and the Council of the European Union 1996). Besides the intention to create an internal European electricity market, the EU expected efficiency gains in electricity supply as a result of higher degrees of competitiveness on the market. The EC laid down some measures to achieve these goals including:

- the enabling of gradually free supplier choice for electricity consumers starting with the largest consumers;
- legal and organisational separation of transmission and distribution activities (unbundling);
- the guarantee of fair and non-discriminative grid access for all electricity generation technologies including new technologies such as RET.

In order to improve the gradual implementation process towards liberalised electricity markets the second legislative package on the internal energy market was adopted in 2003, including a Directive on the gas and on the electricity market (The European Parliament and the Council of the European Union 2003b; The European Parliament and the Council of the European Union 2003c). Regarding electricity markets, the adapted Directive, replacing Directive 96/92/EC, addressed in particular issues with regard to grid accession.

Aiming at a supplementation of the legislative framework conditions regarding the internal energy market, the EC came up with a third “Internal Energy Market Package” to further liberalise the EU’s energy market in September 2007 (European Commission 2007c). The European Council eventually adopted the compromise agreement on the “Internal Market Package” at the end of June 2009 including two directives for the internal electricity and gas markets. Meanwhile, the EC has initiated infringement procedure against 25 of the 27 MS (all MS with the exception of Malta and Cyprus), accusing them for an insufficient implementation of the EU’s second package on internal energy markets.

After controversial discussions a compromise on the issue of ownership unbundling was achieved. Finally, vertically integrated electricity suppliers were not obliged to sell their electricity grid subject to certain conditions. These conditions include a separation of their transmission networks from production activities and an independent operation of both activities.

Aiming at a more effective regulation of the energy markets, it was planned to create an EU agency for the cooperation of energy regulators. In order to increase cross-boarder activities on the gas and electricity markets, the legislation foresees a European Network for Transmission System Operators (ENTSO) in the gas and in the electricity sector. By stimulating the increased cross-border trade of gas and electricity, this legislation was expected to lower energy prices for consumers.

With regard to consumers the package established stronger rights for them, enabling the change of gas and electricity suppliers within three weeks without charges. By means of the amended legislation regarding EU energy markets the EU engaged national governments to provide access to electricity for all households in order to avoid energy poverty for poorer customers. The intention to implement smart metering systems in 80 % of the households by 2020 completed this legislation package.

Now, the upcoming realisation of the proposed rules still have to show whether are able to make progress towards a truly integrated European energy market. The new regulation establishing common the rules for the internal market will come into force by March 2011 (The European Parliament and the Council of the European Union 2009b).

2.1.2 Climate change mitigation and adaptation

Fossil-fuel based conversion processes, required to provide final energy, apparently contribute considerably to global warming as a consequence of the related emissions of greenhouse gases (GHG), such as carbon dioxide (CO_2). In the light of the potential negative impacts of anthropogenic climate change on the global ecosystem, the United Nations (UN) developed strategies to mitigate climate change. In a first step the UN Framework Convention on Climate Change (UNFCCC) was adopted during the Earth Summit in Rio de Janeiro in 1992 in order to encourage industrialised countries to stabilise GHG emissions. Five years later, the Kyoto Protocol, which stipulates legally binding targets to diminish GHG emissions, was adopted (United Nations Framework Convention on Climate Change [UNFCCC] 1997). Thereby, the EU committed itself to reducing domestic GHG emissions to 8 % of its 1990 levels until 2012. Although the Kyoto Protocol has not been ratified by all Annex I countries[1], such as the United States, it came into force in 2005. In addition to the option of meeting the targets through national policy measures, the treaty from Kyoto and the 'Marrakesh Accords'[2] enabled three market-based mechanisms in order to facilitate international cooperation and a reduction in the cost of target achievement.

1 Annex I countries reflect the industrialised countries of the world and include all active members of the OECD as of 1992 and countries with economies in transition (Russian Federation, Baltic States, some Central and Eastern European countries).

2 The Conference of the Parties 7 (COP) agreed on the 'Marrakesh Accords' in 2001 establishing the implementation details for the use of flexible mechanisms

These flexible mechanisms include:

- an international emission trading scheme;
- clean development mechanisms (CDM), which enables industrialised countries, as stated in Annex I to count emission credits for target compliance, if they invest in emission-reduction projects in developing countries (Non-Annex I parties);
- joint implementation (JI), which enables Annex I countries to count emission credits for target compliance if they invest in emission-reduction projects in other Annex I countries.

The EC started a 'GHG Emission Trading Scheme' (EU ETS), as described in Directive 2003/87/EC, in 2005 (The European Parliament and the Council of the European Union 2003b). Private companies represent the obliged parties and were prevailingly allocated emission rights for free, as established at national level in the National Allocation Plans (NAP) during the first trading period from 2005 to 2007 and during the second period lasting from 2008 to 2012. With regard to the third trading period starting in 2013, the EC foresees several changes including a centralisation and harmonisation of cap-setting and allocation rules on EU level. In contrast to the former design of the ETS, auctioning of emission rights will be the main allocation rule. While power plants will face full auctioning as of 2013, the industry sectors will face a slow face-in into auctioning. The share of freely allocated emission rights to the industry will decrease from 80% in 2013 to 30% in 2020 and 0% in 2027. In addition, the free allocation of allowances will be determined based on an EU-wide standardised benchmarking procedure. In order to achieve the goals regarding climate policy, the EC laid down a 'Strategic Energy Technology Plan' (SET-Plan) to enhance the technical development and the market diffusion of promising and cost-effective low-carbon technologies in the future (European Commission 2007a).

In the light of the approaching period after the Kyoto Protocol, European climate policy started to address longer term targets up to 2020 and beyond. The EU agreed on a new energy and climate strategy to restrict global temperature increases to less than 2°C above pre-industrial level in December 2008. This 'climate and energy package' is based on a first proposal of the EC from early 2007 (European Commission 2008a) and includes the following main objectives:

- GHG emission reductions of 20 % by 2020 or up to 30 % in case an international agreement on climate change can be achieved and other developed countries make comparable efforts;
- Improvement of 20 % in energy efficiency by 2020;
- Increase the use of renewable energy sources in energy consumption to 20 % by 2020.

The final legal text of the energy and climate package was eventually adopted in spring 2009. Several measures of how to achieve the targets are formulated in the package. These measures include the revision of the EU-ETS, which will enter into force after 2012.

EU climate policy has been focussing strongly on policies with regard to mitigating climate change so far. Owing to an increasing occurrence of extreme weather phenomena, such as heat waves, floods or storms, the EU has recognised the relevance of climate change impacts for the European ecologic, economic and social system. In this context, the EC published the green paper 'Adapting to climate change in Europe –

options for EU action' in summer 2007 suggesting some policy measures to cope well with unavoidable damages provoked by climate change and to reduce the associated costs (European Commission 2007b). In addition, the EC called for taking early action in the EU and to deal with adaptation issues occurring outside the EU. Subsequently, the EC set out a framework to lessen the EU's exposure to climate change impacts in its white paper released in spring 2009 (European Commission 2009). In this white paper the EC calls for improving the knowledge stock on issues of adaptation to climate change and proposes the integration of adaptation into EU policies. A comprehensive adaptation strategy is planned to be developed from 2013 on.

2.1.3 Security of supply

Owing to the scarcity of oil and gas resources in the EU and to diminishing reserves in the North Sea, the EU is highly dependent on imports of energy carriers from third countries. Thus, the EU is exposed to risks regarding the supply or price fluctuations of the imported energy resources. Intending to ensure an uninterrupted and economic electricity supply, the Commission addressed the issue of securing European energy supply in the green paper 'Towards a European strategy for the security of energy supply', published in 2000 (European Commission 2000). In this paper, the EC identified the subsequent three crucial concerns so as to Europe's security of supply:

- a high degree of dependence on imports of energy sources;
- a limited influence of the EU on energy supply, but realistic options for taking action on the demand side;
- existing problems with regard to the fulfilment of the Kyoto targets.

In their green paper the EC proposed the application of demand side policies, the extension of transmission capacities and a strengthened use of RES to tackle the concerns identified. In addition to its environmental benefits the use of RET may contribute to increasing energy security. Amongst others this fact is attributed to the indigenous availability of RET. At the same time, an increased use of RET involves certain risks to energy security. To put an example, an increased use of wind power plants and its fluctuating electricity output poses important challenges on system management and the existing electricity grid.

After security of energy supply had been identified as one of the core elements of European energy policy in the green paper 'A European Strategy for Sustainable, Competitive and Secure Energy' (published in 2006, see section 2.1), the EC proposed an "'Energy Security and Solidarity Action Plan' in the context of the second strategic energy review in November 2008.

2.1.4 Renewable energy policies

2.1.4.1 Development on European level

The interest of several industrialised countries for RET was sparked first as a result of the oil crises in the 1970s, followed by some few efforts to develop RET including in particular research and development

(R&D) programmes. Though, decreasing oil prices led to a diminishing interest in RET and RET-deployment could not be fomented on a larger scale. The merit of RET was rediscovered in the light of the discussion about climate change and was picked up by the EU in the 1990s. Increasing the share of RET in energy supply was quoted as a core objective of the EU for the first time in 1997 in the white paper 'Energy for the future: Renewable sources of energy' (European Commission 1997) due to the potential contribution of RET to climate protection and the security of supply in Europe. In fact, this White Paper represented a declaration of intent and did not yet include a call for taking concrete action. National indicative targets for the use of RET in the electricity sector were stipulated in Directive 2001/77/EC in order to provide 21 % of the total electricity consumption in the EU-25 using RET by the year 2010[3] (The European Parliament and the Council of the European Union 2001). The decision, how to design the policy measures applied to achieve the targets, was left to the individual MS. Consequently, different types of policy measures have been applied in MS since then, involving an active policy debate about which policies appear to be the most appropriate for the support of RET. According to a monitoring report (COM(2005)627) published by the EC some MS have been more successful than others in promoting RET (European Commission 2005). The analysis of the EC is based on a set of indicators measuring the effectiveness and the efficiency of support schemes[4]. Similar to the findings of COM(2005)627, an updated evaluation judges well-designed FIT to be generally the most effective and efficient policy measure for supporting RES-E (European Commission 2008b).

Looking at the political development in the other sectors, targets for the use of biofuels in the transport sector were established in the 'Biofuels Directive' aiming at a 2 % market share for biofuels by 2005 and 5.75 % by 2007 (The European Parliament and the Council of the European Union 2003a). In the area of heating and cooling, no sector-specific legislation has been introduced yet.

Political developments with regard to the overall energy sector moved on with a discussion about longer term targets. In this light, the European Parliament proposed a target of 25 % for RET in total EU energy consumption by 2020. Subsequently, in early 2007 the EC published its long-term strategy beyond 2010 and proposed to establish a target of 20 % RET share in energy consumption for the first time and a minimum target of 10 % for biofuels as part of the EU’s energy and climate package (European Commission 2007d). In contrast to the Directive 2001/77/EC, this new proposal set up targets for the whole energy sector and not only electricity. In addition, targets were declared binding and not only indicative, as in Directive 2001/77/EC. This EC’s proposal was approved by the Council of the European Union in March 2007.

After the Commission came forward with a proposal on a directive in early 2008, the European Parliament endorsed this proposal at the end of the year. The Directive 2009/28/EC translated the required increase of the share of energy from renewable resources from 8.5 % in 2005 to 20 % in 2020 into individ-

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3 The target was updated in 2007, when Bulgaria and Romania joint the EU, to 22 % for the EU27.

4 Background information regarding the used indicators is provided by Ragwitz et al. (2007), Held (2007) and Held et al. (2006).

ual targets for MS (The European Parliament and the Council of the European Union 2009a)[5]. In contrast, the minimum target of 10 % share of RES in the transport sector was transferred without changes to each MS. In order to ensure a sustainable use of biofuels, sustainability criteria were established.

With regard to the target setting procedure the underlying calculation criteria were based on a flat rate approach on the one hand, stipulating a basic additional share of RET by 5.5 % against 2005 for each MS, and the remaining increase to reach the targets was allocated to the countries according to the national gross domestic product per capita (GDP/capita) on the other hand.

Similar to the former electricity Directive 2001/77/EC the national design of the policy measure applied to achieve the targets still was conceded to MS. These are committed to present “National Renewable Energy Action Plans” (NREAP) with an indicative pathway of how the national target shall be reached by June 2010. Thereby, the expected contribution of each of the three sectors electricity, heating and cooling, and transport, has to be specified. In order to guarantee continuous progress towards achieving the target, interim targets were set. Accordingly, 20 % of the increase should be achieved on average between 2011 and 2012, 30 % between 2013 and 2014, 45 % between 2015 and 2016, and an increase of 65 % is expected on average for the period between 2017 and 2018, respectively. No penalties are due if interim targets cannot be met by MS. Though, the EC reserve’s its right to induce infringement procedures if it considers the policy measures of a certain country not to be appropriate to stimulate sufficient growth of RET. The claim of the Italian government to implement a review clause by 2014 with the option to correct the targets was rejected eventually.

One further important key element of the new directive is related to the question as to how targets can be achieved in a preferably cost-effective way. Since the target setting procedure did not take into account existing heterogeneity in national renewable potentials and in the specific energy conversion costs related to an additional use of RET, MS are allowed to exchange energy from renewable sources to a limited extent. Free trading of renewable energy certificates was discarded.

5 National targets for the share of renewables in gross final energy consumption are shown in Table A-1 in the Annex.

The so-called flexibility measures facilitate the following three options:

- Statistical transfers between MS, if the selling country has fulfilled its own target;
- Joint projects between MS or joint projects between MS and third countries whereby green electricity from outside the EU has to be imported physically;
- Joint support schemes between MS.

The core concepts of the main existing policy approaches are shortly summarised subsequently.

2.1.4.2 Categorisation of renewable support instruments

Various approaches for the promotion of RET have been applied for years in EU-MS. In principle, these policy measures intend to compensate the comparatively high conversion costs of RET and represent thus one central driver of RET development. In principle, one can distinguish between direct and indirect policy instruments. Direct policy measures attempt to stimulate RET directly, whilst indirect measures rather pursue the improvement of framework conditions from a long-term perspective. Besides regulatory instruments, there are voluntary approaches to the promotion of RES-E. The latter approach is mainly based on the consumers' willingness to pay a premium for green electricity. Further important classification criteria are whether policy instruments address price or quantity, and whether they support investment or generation. Table 2-1 provides a categorisation of existing promotion strategies for renewables according to the criteria mentioned.

Table 2-1 Categorisation of policy measures

		Direct		**Indirect**
		Price-driven	**Quantity-driven**	
Regulatory	**Investment focused**	• Investment incentives • Tax credits • Low interest / Soft loans	• Tendering system for investment grant	• Environmental taxes • Simplification of authorisation procedures (connection charges, balancing costs ,...)
	Generation based	• (Fixed) Feed-in tariffs • Fixed Premium system • Production tax incentives	• Tendering system for long term contracts • Tradable Green Certificate system	
Voluntary	**Investment focused**	• Shareholder Programs • Contribution Programs		• Voluntary agreements
	Generation based	• Green tariffs		

Source: Based on Haas et al. (2004)

Feed-in Tariffs (FIT) represent a generation-based price-driven approach. This means that a price per unit of electricity is predetermined by the government and has to be paid by the obliged actor, mostly represented by a utility or the grid operator. This FIT may take form either in terms of a fixed global tariff substituting the market price or in terms of a premium paid on top of the market price. In some cases, the time horizon a tariff is conceded for, is fixed and provides therewith additional planning security for potential investors. Generally, FIT allow for a technology-specific promotion of RET as well as for the stimulation of future cost reductions by considering certain criteria within the specific design of a FIT.

In contrast **Quota Obligations based on Tradable Green Certificates** (TGC) follow a generation-based but quantity-driven approach. Instead of predefining the price, a quota is established first by the government. This quota then has to be fulfilled by one particular actor of the electricity supply chain, e.g. generators, suppliers or consumers. Subsequently the certificate price results as a consequence of matching supply and demand in a market for TGC. The arising certificate price serves as one revenue component in addition to the electricity market price. A penalty level may be defined, which has to be paid if some of the obliged parties cannot prove quota fulfilment. In theory, there are different options of how to implement a technology diversification within the TGC systems. However, these options involve several problems, as e.g. a loss of liquidity if markets are split up. A weighting of certificates according to the respective technology option and its financial requirements may impede the target setting and complicate the monitoring process of target fulfilment.

Tendering systems are assigned to quantity-driven mechanisms focussing either on the support of investment or generation. In both options a predetermined amount of capacity to be built is proclaimed. Following a bidding procedure, the winning bidders are provided with financial support either in terms of investment incentives or remuneration per unit of electricity produced.

Investment incentives assume a fixed proportion of the overall investment that has to be raised in order to finance a RES project. The corresponding share tends to be specified in a technology-specific way.

The exemption of RET from conventional taxes is generally known as **production tax incentive**, a generation-based and price-driven approach. In contrast to the FIT, it represents a kind of negative costs instead of providing additional revenues.

2.1.4.3 Development of national support measures for promoting renewables

This section outlines the main developments of support policies applied to stimulate an increased use of RES in the electricity sector at national level. Observing the evolution of the main support schemes (compare Figure 2-1) it becomes clear that FIT and quota obligation systems dominate the applied support schemes. Therefore, the current discussion within EU MS focuses on the comparison of FIT and the quota obligation. The latter replaced existing policy instruments in Belgium, Italy, Sweden, the United Kingdom, Poland and Romania. Policy schemes such as tender schemes are no longer used in any European country as dominating policy scheme. Ireland, as a prominent example of a country applying a tender scheme, replaced it with a FIT system due to problems with strategic bidding behaviour. To some extent tendering schemes are used in certain MS for specific projects on a technology level (e.g. offshore wind in Denmark). Further policy measures such as production tax incentives and investment grants represent the dominating policy measure in Finland and in Malta. In some other countries they are used as a kind of supplementary support.

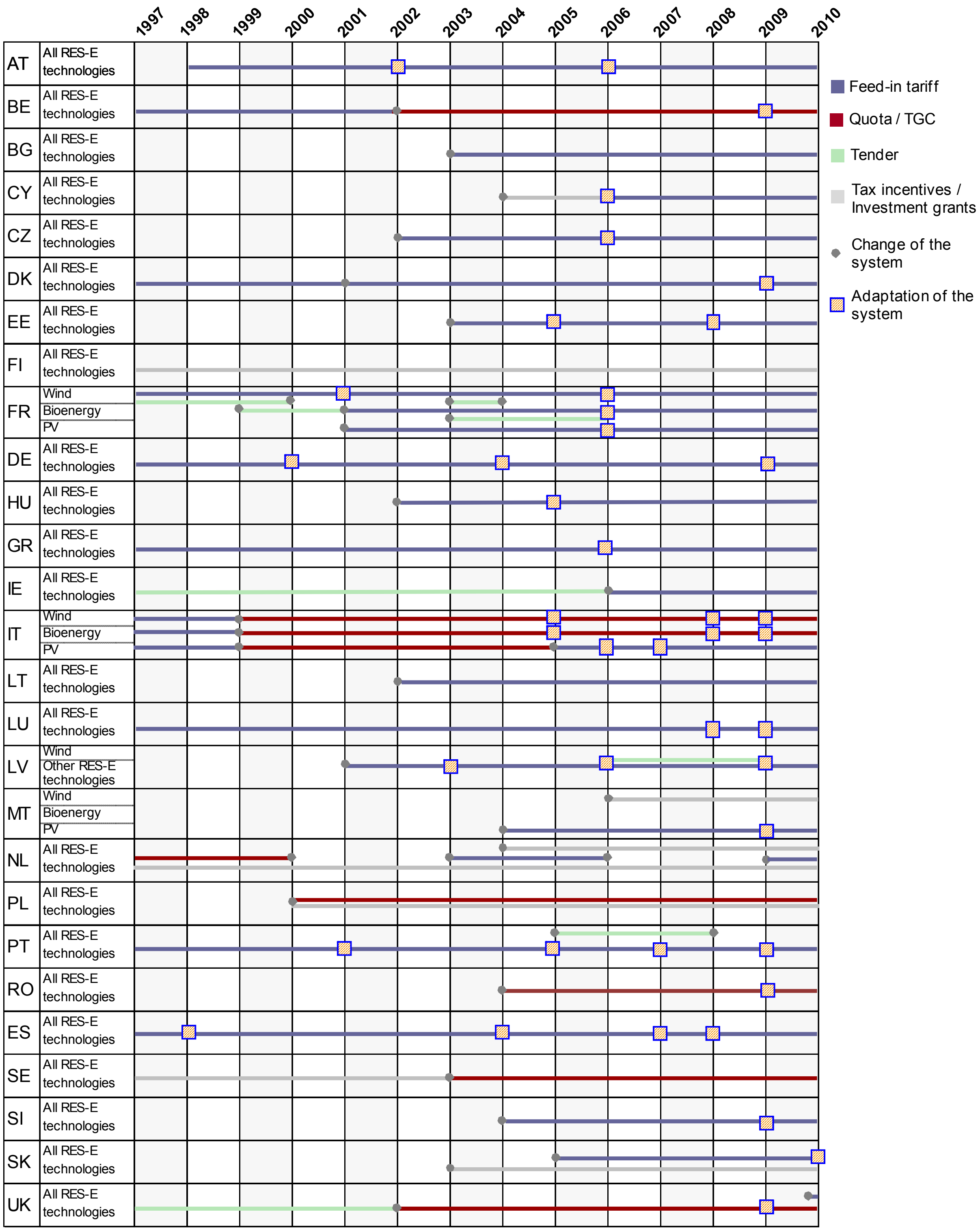

Figure 2-1 Evolution of the main policy support scheme in EU27 Member States

Source: Own illustration

2.1.5 Implications of European policy on the renewable energy market

Induced by the liberalisation process, fair and non-discriminative grid access is provided to all technologies including emerging RET. Together with the implementation of national support policies in several countries it provided the basis for the beginning market development of RET in the electricity sector. However, only some countries, such as Denmark or Germany, achieved a considerable deployment of RET in particular with regard to onshore wind energy as a consequence of their national policy support schemes before the European policy makers took up RET on their agenda. In the light of the RET's potential contribution to mitigating climate change and to reducing import dependency on fossil fuels the relevance of RET for European policy makers has been increasing steadily over the last decade. In this way, the EC set up the legislative framework conditions for the support of RET in the electricity market by establishing indicative targets for an increased share of RET by 2010, and in the transport sector by the introduction of minimum quota for biofuels. Whilst RET have been developing dynamically in the electricity and the transport sector so far, missing legislation in the heating and cooling sector appeared to impede a stronger market development of renewable heating and cooling technologies. Only Directive 2009/28/EC provided a common legislative policy framework on EU level for all three sectors. The commitment to longer-term targets up to 2020 contributes to providing security for potential investors in RET. However, missing targets on sectoral level might hamper the monitoring of interim target achievement. Thus, sectors might put the blame on others in case the targets cannot be achieved.

Generally, the legislative framework on EU-level in combination with the implementation of national renewables policies featured Europe to become one of the leading markets for RET. The ETS alone has not been able to make most RET competitive with conventional energy conversion technologies so far. Consequently, there are no impacts of the ETS on RET at present, but with rising carbon prices, it might substitute sectoral renewables policies in the long-term.

2.2 Market development of renewable energy technologies in Europe

As a consequence of existing policy support on European and national level the RES-market in Europe has been developing dynamically, showing considerable growth rates in recent years. To cite an example, wind capacity has been experiencing impressive growth rates in Europe, which have primarily been observed in Denmark, Germany and Spain. The data presented within this section has been collected from several statistical sources. It is mainly based on statistical data from Eurostat and is complemented with information from EurObserv'ER and the International Energy Agency[6] (EurObserv'ER 2009; Eurostat 2010; International Energy Agency [IEA] 2009).

Looking at the development of RET in the three final sectors electricity, heat and transport, as shown in Figure 2-2, it becomes clear that the output of renewable heat dominates the renewable final energy mix

6 Data from Eurostat is publicly available at http://epp.eurostat.ec.europa.eu, data from EurObserv'ER at http://www.energies-renouvelables.com/barometre.asp.

representing a proportion of 54 %. RES-E generation contributes 38 % to total final energy consumption based on RES, whereas the transport sector still plays a marginal role. The overall share of RES in final energy consumption slightly rose from 6 % in 1990 to roughly 11 % in 2008. However, taking into account the target of 20 % by 2020, further strong efforts to stimulate the market development of RET are required, if targets are to be fulfilled.

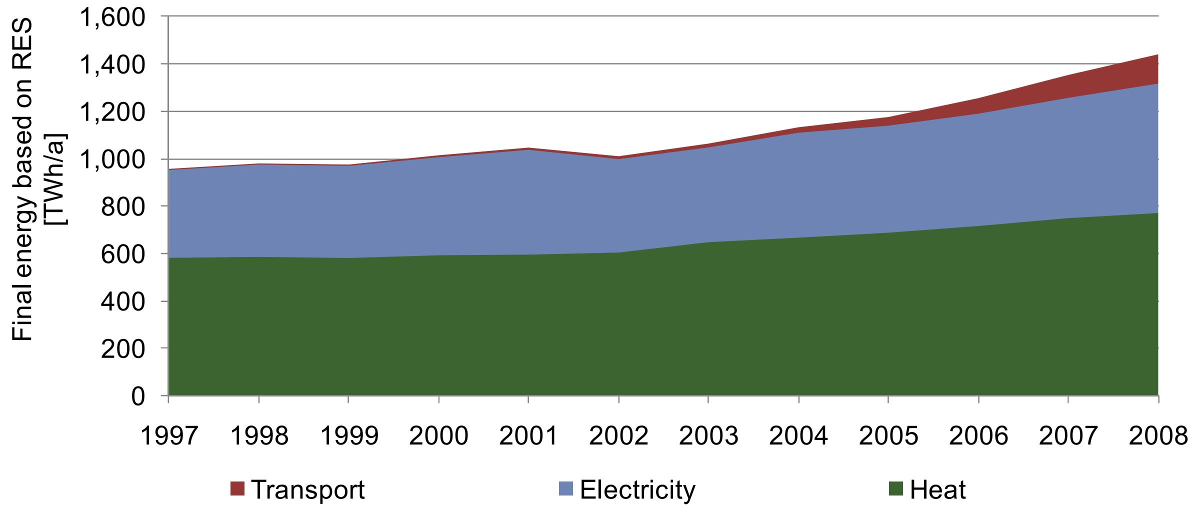

Figure 2-2 Market development of RET according to final energy sector (EU27)
Source: Own illustration based on data from Eurostat, EurObserv'ER and IEA

In recent years, RES-E generation has been increasing slightly (Figure 2-3). Hydropower still represents the dominant RES, but has become less important during the last years. This fact is caused by a strong development of emerging RET, such as wind and biomass. Whereas hydropower accounted for 94 % of RES-E generation by 1990, the overall share of hydropower in total RES-E generation decreased to 59 % by 2008. Looking at Figure 2-3, it becomes apparent that the electricity output from hydropower fluctuates annually due to changing meteorological conditions.

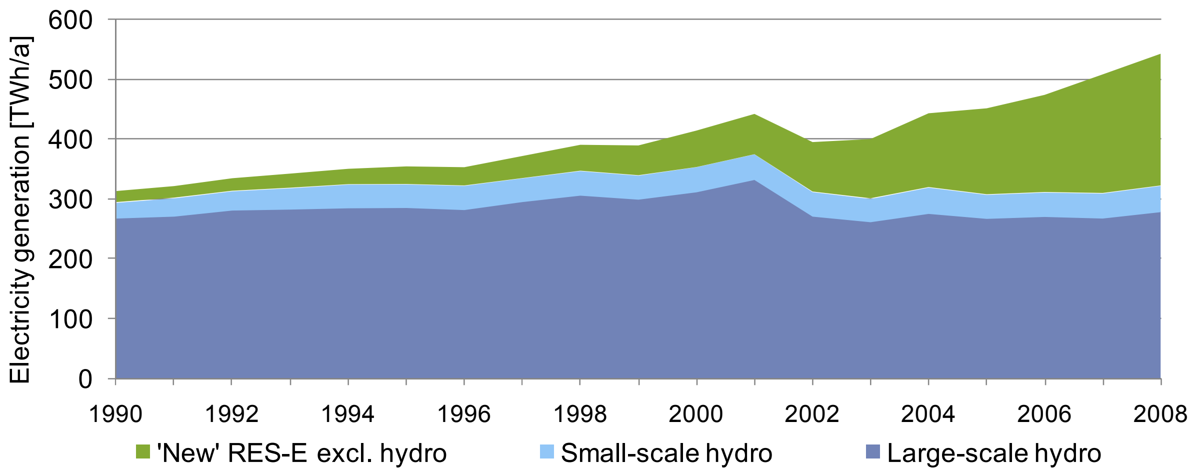

Figure 2-3 Market development of RET in the electricity sector (EU27)
Source: Own illustration based on data from Eurostat, EurObserv'ER and IEA. Data presented for the year 2008 are preliminary data or based on estimates.

Focussing on the development of "new" RES-E[7], electricity generation increased more than tenfold from 19 TWh in 1990 to 223 TWh in 2008 as a consequence of policy efforts made on European and at national level (cf. Figure 2-4). Thereby, in particular onshore wind and the use of solid biomass contributed significantly to this development. In contrast the development of offshore wind still appears to be behind expectations.

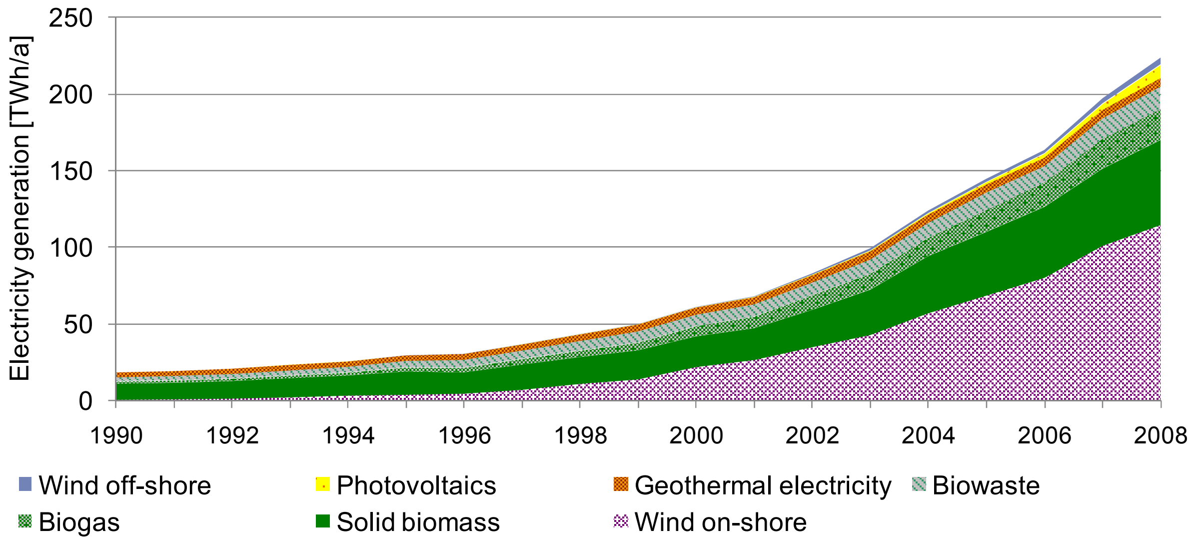

Figure 2-4 Market development of 'new' RET in the electricity sector (EU27)

Source: Own illustration based on data from Eurostat, EurObserv'ER and IEA. Data presented for the year 2008 are preliminary data or based on estimates.

Looking at the relevance of RES-E generation within the overall power sector in Europe (see Figure 2-5), one should note that the share of RES-E in gross electricity consumption increased slightly from 13 % in 1997 to 16 % in 2008. This fact appears to conflict with the increasing trend of new RET in the electricity sector, but it can be explained by the following reasons. First, existing variations in the annual hydropower output implicated slightly less hydropower generation in 2008 compared to 1997. Second, European gross electricity demand has been rising during this time horizon by more than 30 %. Comparing the RES-E penetration in 2008 with targets set within Directive 2001/77/EC additional efforts have to be made to reach the target of 21 % by 2010.

7 As hydropower has been used for a long time and its resources are almost exploited, its development is much less dynamic than those of the other RET. The development of "new" RET excluding hydropower is shown to better show the dynamics of the emerging RET.

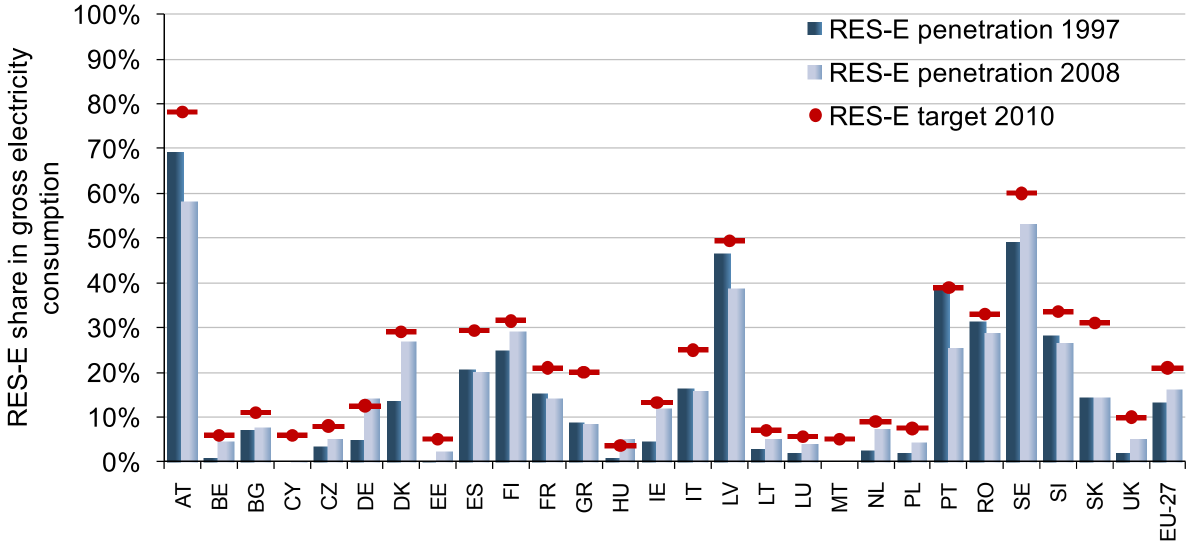

Figure 2-5 RES-E share in gross electricity consumption as compared to targets by 2010
Source: Own illustration based on data from Eurostat, EurObserv'ER and IEA

2.3 Impacts of climate change on the use of renewable energy sources

While the use of RET might contribute significantly to mitigating climate change, some RET are also vulnerable to changes in global climate. The increase in CO_2 concentration involves changes in temperature, precipitation patterns, evaporation, wind speeds and cloudiness, which again may have an impact on the use of RES. Temperature changes may have a direct influence on the available RET, such as solar irradiation, wind speed or changes in river discharge volumes. As a result the capacity factor of a RES-E plant may be affected, implying a modified power output. As RET electricity is characterised by a high share of investment in total electricity generation costs, the related impacts on average electricity generation costs can be substantial and can greatly influence the competitiveness of RET in the conventional electricity market. Besides the total amount of electricity produced, climate change may have an impact on the variability of the power output, in particular regarding hydropower plants or wind turbines. Growth characteristics of woody and agricultural biomass plants may be affected by changing temperature, as well as by an increased CO_2 concentration in the atmosphere. Temperature increases may also affect characteristics of the applied conversion technologies, for instance, regarding the solar cell efficiency of PV plants. A higher module temperature is generally accompanied by a reduction of solar cell efficiency.

Regarding the representation of the future RET development in Europe within a simulation model, a quantification of climate change impacts on RET is suggested. However, the quantification of climate change impacts on RET presents a challenging task. Impacts can be quantified using input from climate data predicted commonly by general circulation models (GCM). Uncertainties related to the GCM-predicted changes in global climate imply that derived results are only of an exploratory character. Furthermore, the resolution of climate models is often too coarse to model their impact on the availability of RET, for instance, regarding the prediction of wind speeds. The refinement or local downscaling of GCM output represents one approach towards improving geographical resolution. Detailed consequences of climate change on the use of RET will be discussed subsequently.

2.3.1 Wind energy

The productivity of wind electricity generation is predominantly characterised by a high dependency on local wind regimes. More precisely, the power output of a wind turbine is proportional to the cube of the wind speed. For this reason, even small changes in wind speed, possibly caused by climate change, may have a considerable impact on the power output of a wind turbine, thus leading to a modification of the total available wind energy potential.

Wind power is further characterised by fluctuations and a certain unpredictability of the power output. To a certain extent, the impact of climate change may represent an additional risk for wind power investments, reinforcing existing uncertainties regarding the total amount of electricity generated by a wind turbine.

Climate change is expected to induce an increase in extreme wind speeds and calms, on the one hand, and induces changes in mean wind speeds on the other hand. At this point the focus is put on the discussion of the climate change impact on mean wind speeds, as their development is crucial for the potential future magnitude of the electricity output generated with wind turbines.

In particular, the quantitative analysis of the impact of climate change on wind power represents a challenging task. Existing GCM used to project climate change effects provide data on changes in wind speeds, but the coarse geographical resolution of the models is not sufficient to map a realistic picture of the partly strongly varying wind conditions at a regional level. This fact can be explained by the strong regional dependence of wind power regimes and thereby a strong regional dependence of the climate change impacts on wind power. In addition, wind speed accuracy with an error of ±1m/s which is regarded as quite accurate may lead to considerable differences in the resulting power output.

After the majority of the existing climate change studies focussed on the description of precipitation and temperature effects, an increasing number of studies has been carried out to investigate the potential effect of climate change on wind power in recent years. To the authors' knowledge, there is no study available covering Europe as whole at a national level at present. The first studies in this field focussed regionally on the USA, Scandinavia and the United Kingdom. Recently, further work has been carried out to analyse the impact of climate change on German wind speeds. However, most of the scientists still point out the explanatory character and the high degree of uncertainty of the obtained results.

In most of the cases, data output from GCM models is employed within this analysis in order to represent changing climate conditions. As the comparatively coarse geographical resolution of the GCM models tends to be insufficient for the analysis of wind power potential, refinement methodologies are used in order to downscale the global climate data and convert it to a higher disaggregated regional level. Common methodologies represent empirical or statistical geographic downscaling. Indeed, downscaling in principle does not allow for dealing with small-scale effects.

Some of the first studies carried out in the field dealt with climate change and wind energy in the USA. In order to estimate the impact of climate change on wind power potential Segal et al. (2001) used a refined regional climate model based on HADCM2 outputs. The explanatory results of this study indicate a seasonal reduction of wind power potential by 0 % to 30 % and an annual change of about ±10 %, assuming a hub height of 40 m. At the same time, the authors found that the Southern and North-Western part of the USA seems to experience an increase in wind power potential of up to 30 %. Furthermore, the wind power potential appears to remain unaffected by climate change in regions with favourable wind conditions.

Breslow & Sailor (2002) estimated the potential impacts of climate change on wind regimes in the USA, using the general circulation models from the Canadian Climate Center and the Hadley Center (HADCM2). The authors predict a decrease in wind speed of 1.0 % to 3.2 % by 2050 and 1.4 % to 4.5 % by 2100 at an altitude of 10 m. In this study, climate output data is used without applying any downscaling technique. The authors highlight the uncertainty of predictions, in particular for the time horizon after 2050. However, the authors do not make any statement about the evolution of the wind speed at turbine height of about 60 m to 100 m. As wind speed rises with increasing distance from the surface, depending on the roughness of the ground wind speed, information on changes at hub height would be necessary in order to evaluate the concrete impact on power output.

In a more recent article Sailor et al. (2008) put the focus on the estimation of the climate change implications on wind power in five concrete sites within the North-Western United States. In order to improve regional data quality of the GCM data, statistical downscaling was applied. The resulting validation of statistically downscaled climate output data against real data from selected sites showed a significantly improved data consistency as compared to the original data output. In a next step, the authors scaled up wind speeds to a hypothetical hub height of 50 m and derived the changes in monthly power densities. The results show a decrease in wind power potential of up to 40 % in spring and summer, whereas results for winter seem to be less consistent, indicating, however an increase in future wind power potential.

Another piece of research was carried out by Venälainen et al. (2004) who analysed climate change impacts on the Finnish energy system. Results based on the hub-height corrected offshore wind speed data from the GCM HADCM3 model indicate an average increase of offshore wind power potential by 2 % to 10 %, representing a rise of 20 % to 30 % in winter and 10 % to 15 % in summer time.

The British authors Harrison & Wallace (2005) intended to approximate a range of potential climate change vulnerability of wind and wave power potential using sensitivity analysis without considering country-specific GCM-derived future climate data. In a very recent study Harrison et al. (2008) went one step further and applied British climate data in order to investigate changes in wind speed induced by climate change. The authors built their analysis on HADRM3-ouput, representing a regionally refined equivalent of HADCM3. Results indicate slight averaged changes on an annual basis, and seasonal and geographical differences. According to the authors the annual mean wind speed increased by 0.5 % up to 2080. Seasonal wind speeds augmented by 5 % to 10 % in the South and East of the UK, while slight reductions were projected for the North of Scotland and Northern Ireland. At the same time, summer wind speeds were predicted to decline by 5 % to 10 %. The Scottish Road Network Climate Change Study carried out by Galbreith et al. (2005) reports on expected changes in two-year daily mean wind speed amounting to a magnitude of ± 5 % for Scotland.

Results from an investigation carried out by Pryor et al. (2006) for Scandinavia and the Baltic States based on climate data from HADCM3 indicate that there appears to be no considerable change either in the evolution of annual wind indices nor in the seasonal differences.

Recently published results of a project investigating climate change in Germany indicate that there will not be an increase in frequency of extreme wind events including days with a mean wind speed exceeding 10 m/s (Jacob et al. 2008). Regarding average wind speeds, the authors expect no change in the annual means and only moderate changes at a seasonal level. Wind speeds are estimated to increase slightly in some months by up to 0.4 m/s up to 2050. Looking at the time frame up to the end of the 21st century, wind speeds in Germany seem to rise slightly in winter, whilst a low decrease is foreseen for the summer months.

To the authors' knowledge, there are no studies providing detailed results on climate change impacts for Europe as a whole. In an analysis carried out by Watson et al. (2002), trends of offshore wind speeds over the past 40 to 100 years for the European Atlantic, the Baltic Sea and the Mediterranean were observed, without predicting any changes for the future. In another study the impact of climate change on wind power is estimated for Europe with a focus on German wind speeds, again without providing detailed geographical results. The research consortium made projections of mean changes in wind speeds by the end of this century, based on three regional climate models (Walter et al. 2006). The authors observe an increase in annual mean wind speeds at 10 m height during winter over Europe, with a strong increase in the Baltic and North Sea, a decrease in the Mediterranean area and a decrease in summer. Annual means seem to increase by up to 1 m/s in the Baltic Sea and decrease by about 1 m/s in the Mediterranean area on average.

2.3.2 Hydropower

The driving force for the hydropower potential affected by climate change represents the discharge volume of rivers, which is mainly induced by changing precipitation patterns and evaporation. While precipitation changes may show increasing as well as decreasing trends, depending on the geographical area and the season, evaporation is expected to rise due to ascending temperatures. Hence, considerable changes in discharge regimes are expected for the future as a consequence of climate change.

In this context, Lehner et al. (2005) estimated the impact of climate change on hydropower potential for Europe on a national scale. The authors calculated the influence of climate change on the gross hydropower potential as well as its impact on the already developed hydropower capacity. Results obtained in the analysis mentioned indicate that discharge volumes for Southern and East-Central Europe may decrease in parts by more than 25 %, whilst foreseen rises in discharge volumes for Northern European countries may in part exceed 25 %. In addition, one should consider that hydropower production is characterised by a high annual variability which may even provoke higher changes on an annual basis.

In accordance with the described results, Venälainen et al. (2004) estimate an increase in hydropower production in Finland amounting to between 7 % and 11 %. Results are based on hydrological modelling for three hydropower plants which represent 70 % of Finnish hydropower production.

Another article describes the impact of climate change on hydropower plants in Switzerland. Hauenstein (2005) discusses, in a mainly qualitative manner, the impact of climate change on hydropower plants in Switzerland, focussing on the impact on Alpine hydropower plants. As compared to the impact on the productivity of common hydropower plants, Alpine hydropower plants are affected differently by climate change. First, an increased hydropower production in summer provoked by melting glaciers is foreseen, until several glaciers may have disappeared. On the other hand, stronger precipitation in form of snow expected during wintertime might increase river flow in spring and early summer. Then, an increasing share of rainfall in precipitation in wintertime will be directly available for hydropower production, while less hydropower is expected for summer, due to decreased precipitation in summer and diminishing snow reserves.

2.3.3 Other renewable energy sources – photovoltaics and biomass

Photovoltaic electricity generation may be affected in two ways. First, a possible change in solar irradiation affects the utilisation of a PV power plant, leading to a modified electricity output. The change in solar irradiation may occur as a consequence of changed clouding possibly induced by climate change. Given the difficulty to model and predict long-term changes in clouding, the estimation of this effect represents a very challenging task and cannot be provided within this thesis. The other effect is related to efficiency losses caused by a temperature increase in the PV module as described by Nordmann & Clavadetscher (2003).

Climate change influences the availability of biomass in different ways. While an increased CO_2 concentration tends to influence positively most of the existing crops, changes in precipitation patterns or temperatures may favour or prejudice crop productivity (Tubiello & Ewert 2002). Results from a modelling exercise carried out by Olesen et al. (2007) indicate a rise in crop productivity in Northern European countries as a consequence of longer growing cycles and higher CO_2 concentrations. Compared to that, crop productivity may decline or increase only slightly in Southern European countries due to changing precipitation patterns. In this way, the biomass potential in Finland is estimated to increase by about 10 % to 15 % (Venäläinen et al. 2004).

3 Modelling approaches for the diffusion of renewable energies

Motivated by the high complexity of diffusion processes of RET, the use of a quantitative modelling approach is suggested to estimate the potential contribution of RET to a sustainable European energy system and the associated financial impacts. A broad variety of modelling approaches has been applied to examine several problems in the energy sector. It is the objective of the first part of the chapter to identify an appropriate approach for the given problem on the basis of existing concepts. Therefore, the chapter starts with the identification of the requirements for modelling the diffusion of RET. Subsequently, the conceptual background of the most relevant modelling approaches that have been applied in the energy sector is provided. In the context of the long-term modelling horizon of the given problem, the next section provides an introduction into the phenomenon of technology diffusion and technological change. Based on the presented concepts, the suitability of the presented approaches is analysed to motivate the decision in favour of an agent-based simulation approach.

The second part of the chapter deals with the description of the selected modelling implementation options. Some examples of how to consider RET in energy models are presented and discussed without intending to be exhaustive. Thereafter, examples of representing technology diffusion processes within the chosen modelling approach are presented. Since existing applications of agent-based simulation to analyse technology diffusion processes in the energy sector are still scarce, examples outside the energy sector are included. The chapter closes with a summary.

3.1 Requirements for the modelling approach

In order to model the diffusion of RET their characteristics and interaction with the existing environment have to be taken into consideration in detail. Thereby, one should take into account that characteristics of RET may differ from those of conventional energy conversion technologies to some extent. The first reason is that RET are mainly not competitive on the electricity market as long as external costs of conventional energy sources are not factored in.

In most cases RET are not bound to regular market conditions but are strongly influenced by the legal framework and possible system changes. They are exposed to rather restricted competition and do not have to compete with conventional conversion technologies given that financial support is available. Additionally, in most countries the purchase of green electricity is granted. In this context, the central requirements for an approach to tackle the given problem are the following.

First, the modelling of the future RET development requires a **high level of detail** regarding the **techno-economic characterisation** of RET, mainly determined by the available resource potential and the corresponding conversion costs. In particular, the unequal spatial distribution of RES requires an appropriate consideration within the modelling approach. The specification of techno-economic data in the field of RET-modelling tends to be based on the concept of cost-resource-curves, as described by Resch et al. (2004).

Second, the diffusion of RET is determined by the **dynamic development of the applied technologies** over time (Neij 1997). The economic competitiveness of RET might be affected considerably by changing technology characteristics. Consequently, the modelling approach should allow for the integration of dynamic technology options.

The third requirement refers to the adaptability of the approach to integrate a **complex and dynamically evolving policy framework** on national as well as on pan-European level. As the use of RET is predominantly not yet competitive on the market, the financial support provided by various policy measures represent one of the main stimuli for the adoption and diffusion of RET.

Forth, the ability of considering **individual investment decisions** of potential investors should be enabled by the chosen approach. The market development of RES is eventually determined by individual investment decisions of potential investors. Dinica (2006) supports this argument and proposes the consideration of the investor's perspective into the assessment of RES-support policies. The author criticises that most of the current analysis regarding the diffusion of RET do not consider the investor's perspective, but only the policy perspective. Thus, different degrees of risk propensities of various investor types should be taken into account. Investors, acting on the market of RET might pursue strategies different from those pursued in other markets. In this way, investments in RET might be motivated in particular by ecological reasons, and not exclusively by economic considerations. Furthermore, the decentralised structure of RET may involve a rather decentralised decision making than in case of conventional energy conversion technologies, which are characterised by stronger centralisation, and predominantly planned by incumbent utilities.

Fifth, the integration of **market imperfections** should be feasible within the developed approach, since the diffusion of RET is not exposed to perfect market conditions in fact.

Sixth, the integration of **technology diffusion** aspects should be enabled by the applied modelling approach in order to consider the long-term development perspective of a certain technology. This argument is supported by Barreto & Kemp (2008) who suggest the representation of technology diffusion aspects into energy-system models in order to reflect the main drivers for a technology diffusion process. As stated by Jacobsson & Johnson (2000) the market development of RET corresponds to a technology diffusion process which is embedded in the transition to a more sustainable energy system.

Finally, the **practical realisation** should allow for an adequate proportion between modelling output and effort to analyse the given problem. Given the continuously changing framework conditions, **flexibility** should be enabled within the selected modelling approach.

3.2 Modelling approaches in the energy sector

In order to analyse complex real systems consisting of a multitude of interdependent elements, a reduction of the problem by concentrating on the central components of the system appears to be required. This abstraction of a real situation can be realised by means of a model (Scholl 2001, p.15-16). Models have been developed and applied to investigate several types of problems in the energy sector for a long time. Various types of modelling approaches are described in literature, whereas each approach appears to be more or less appropriate for a specific type of underlying problem. In principle, modelling approaches are generally distinguished in bottom-up models and top-down models (Enzensberger 2003, p. 43). Top-down models deal with the representation of macroeconomic patterns including the entire economy as a whole, whilst bottom-up approaches intend to model processes within a specific sector at a higher level of detail. At the same time, bottom-up models tend to neglect feedback loops with other sectors of the economy or represent them in a simplified way. As the modelling of a RET diffusion process requires the representation of highly resolved technological details, the subsequent modelling overview focuses on the description of bottom-up approaches. Bottom-up models in turn can be classified into optimisation and simulation models[8]. One should however consider that there can be hybrid modelling approaches combining the main elements from different modelling categories according to the requirements of the given problem (Enzensberger 2003, p. 54).

3.2.1 Optimisation models

Optimisation models have been applied in order to investigate optimal solutions for a given problem in the energy sector under prevailing framework conditions for a long time. Optimisation models rank among partial equilibrium models as they usually focus on the detailed representation of the energy sector. Potential impacts from other parts of the economy may be considered in terms of exogenous inputs. In general this consideration of interactions of the energy sector with other sectors of the economy takes place without the explicit modelling of existing relationships. In optimising energy models the real energy system is reproduced in terms of a directed graph, whereas edges stand for energy or material flows and nodes represent either conversion plants or grid nodes (Enzensberger 2003, p. 47). Optimising energy models feature a high level of technological detail representing the individual technology options (Fichtner et al. 2003, p. 52). In many cases a linear programming approach, based either on cost minimisation or on profit maximisation, is applied within optimising energy models (Enzensberger 2003, p. 48). Looking at the implementation of optimising energy models in practice, the currently existing optimising energy models can predominantly be traced back to the original model families EFOM (cf. Wietschel 1995), MARKAL (cf. Egberts 1981; Fishbone et al. 1983; Loulou & Goldstein 2004) and MESSAGE (cf. Schrattenholzer 1981). Further development of these model families lead to the model families PERSEUS (cf. Enzensberger 2003; Rosen 2008), TIMES (cf. Remme & Blesl 2008; Remme 2006) and BALMOREL (cf. Cremer 2005).

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8 Enzensberger (2003, pp. 42 - 54) provides an in-depth model comparison including a description of top-down models .

Generally, optimising energy models enable an analysis from the perspective of a centralised planner for the energy or electricity system as a whole and assume a perfect market with perfect information availability. However, recent developments in energy policy including a switch from centralised planning processes to a liberalisation of energy markets pose new challenges to modelling approaches (cf. Olsina et al. 2006; Sensfuss 2008, p. 22). Due to the negligence of real world phenomena as e.g. of market failures optimisation model tend to provide rather optimistic appraisals of the underlying situations by underestimating transaction costs (Wietschel 2000, p. 133). Another problem within optimisation models consists in the fact that small changes in input parameter might lead to considerable modifications in the output, the so-called 'bang-bang' or 'penny-switching' effect (Zhang & Folmer 1998, p. 105). However, there are several possibilities to mitigate problems related to 'bang-bang' effects, as e.g. the setting of additional constraints to exclude unrealistic results or the integration of uncertainty aspects (Rosen 2008, p. 124 - 125).

In view of the incorporation of new technologies into optimising energy systems additional aspects beyond the scope of the optimisation approach can substantially determine the development of the energy system. In this way Grübler (1998) proposes to integrate further driving factors such as uncertainty, research and development, and increasing returns into models dealing with technological change in general (Grübler 1998, p. 91). Likewise, Barreto & Kemp (2008) suggest the consideration of technology diffusion in energy system models.

3.2.2 Simulation models

In contrast to optimisation models, simulation models rather aim at the replication of sequential rules describing interrelationships between different system components than on the identification of an optimal solution. The application of simulation models is suggested by Ventosa et al. (2005) in case the problem under consideration appears to be too complex to be described by a formal definition of equilibrium. Due to their flexible character, simulation models allow for the integration of aspects regarding market imperfections such as strategic behaviour or imperfect information availability. Prominent examples of simulation models are system dynamics (SD) and agent-based simulation (ABS)[9].

3.2.2.1 System dynamics

Models based on the concept of SD, developed in the 1950 by Forrester (1958), attempt to explain the behaviour of a social system as a result of interdependencies between components considering dynamic changes over time. The predetermined stocks and flows represent two central components of the system. Existing interconnections between stocks and flows are established by 'feed-back loops' and can be represented in terms of non-linear differential equations. In contrast to the use of one uniform objective function within optimising energy models, SD allows for a more detailed and flexible representation of exist-

9 Accounting frameworks and game theoretic approaches can also be attributed to simulation models. Since neither of these approaches appears to be suited for the analysis of the given problem, they are not illustrated within this thesis. For a short description of both approaches the reader is referred to Sensfuss (2008, p.27).

ing interdependencies and is able to take into account market imperfections (Enzensberger 2003, p. 50). Applications of SD approaches in the energy sector focussing on the analysis of long-term developments are e.g. the TIME-model investigating long-term structural developments within the worldwide energy system (de Vries et al. 1999), the POLES model replicating the whole energy system (Russ & Criqui 2007) or the ASTRA model in the transport sector (Schade 2004). One crucial weakness of the SD approach consists in the validation and calibration of the assumed feed-back loops, in particular with regard to the modelling of long-term developments (Fichtner et al. 2003, p. 52).

3.2.2.2 Agent-based simulation

As opposed to conventional approaches including equilibrium or optimisation models, ABS is a simulation approach that takes into consideration market imperfections, e.g. strategic behaviour, asymmetric information and non-economic influences. Since the early 1990s the comparatively novel approach of ABS has been increasingly applied to problems in several disciplines to investigate macro-level complexities as a result of interactions on the micro-level (Ma & Nakamori 2005). These interactions on the micro-level consist in decentralised decisions of and interactions between heterogeneous actors or agents in a system (Janssen & Ostrom 2006). Thus, the agent itself plays a central role within ABS. Its architecture originates from the concept of distributed artificial intelligence[10]. However, due to the broad scope of application, no universally accepted definition of the term "agent" has emerged so far in the current literature. In the field of ABS there are several understandings of what specific agents' characteristics mean depending on the specific requirements of the investigated problems in diverse disciplines. According to a commonly used characterisation of agents, provided by Wooldrigde (1995), agents

- are able to act **autonomously**,
- are capable of **interacting socially** with other agents,
- are able to perceive and to respond to their environment or they are **reactive**,
- are capable to take the initiative for an action and are therewith characterised by **pro-activeness.**

Wooldridge (2005) differentiates between optional attributes of agents representing intelligence (e.g. pro-activeness, reactivity, social capability) and a universally applicable notion of the term 'agent' in a more recent piece of work. To mention one example of an optional agent property, the author argues that the agents' ability to learn can be attributed different degrees of importance or may even be disregarded in some applications of ABS (Wooldridge 2005, p. 15). The resulting basic definition reads as follows:

"An agent is a computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to meet its design objectives." (Wooldridge 2005, p. 15)

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10 For more information about distributed artificial intelligence in computer sciences, the reader is referred to Bond et al. (1988).

Likewise, Weiss (2000) perceives agents as the "*computational entity such as a software program (...) that can be viewed as perceiving and acting upon its environment and that is autonomous in that its behaviour at least partially depends on its own experience"* (Weiss 2000, p. 1).

In a notion used within the field of agent-based computational economics (ACE)[11] agents are perceived as *"bundled data and behavioral methods representing an entity constituting part of a computationally constructed world"* (Tesfatsion 2006, p. 835). In addition the author states that agents do not necessarily have to dispose of cognitive abilities (Tesfatsion 2006, p. 835 - 836). Besides individuals, agents can represent aggregation of individual agents, such as social groupings, institutions, biological or physical entities.

Besides the theoretical concepts of ABS, there are different options of how to practically implement and realise ABS. Klügl (2001, p. 100) mentions the option of using predefined simulation tools available, providing a graphical user interface as one alternative and the direct use of programming languages as the second alternative[12]. Thereby, predefined tools tend to be comparatively easy to handle, whereas programming languages require programming skills but are characterised by a higher flexibility. In the latter case the application of object-oriented languages appears to be appropriate due to several similarities between the agent's characteristics and the basic concept object-oriented programming (OOP) approach. In such a way, the modular character of OOP languages is able to represent heterogeneous and autonomous agents.

In particular, earlier work in the field of ABS was mainly characterised by a high degree of abstraction, empirical applications were rare (Janssen & Ostrom 2006). Although empirical examples of ABS have been increasing in recent years, one of the central problems regarding ABS still consists in the difficulty of validating and calibrating the agents' behaviour. Thus, the representation of real-world phenomena based on ABS is still improvable and represents a challenging research field for future work.

According to Axelrod (2006), ABS is applicable to problems in various disciplines and can be described as a multidisciplinary tool. Thus, there are manifold application examples beyond the energy sector that use ABS. Tesfatsion et al. (2006) provides a comprehensive compilation of ABS research in economics (ACE). Exemplary applications of the ABS methodology in the energy sector are described later on in this chapter (cf. section 3.6). As the application of ABS in the energy sector has been focussing predominantly on short-term analysis, examples from other disciplines using ABS for the modelling of technology diffusion patterns are presented as well.

Several examples of agent-based approaches applied to analyse problems of technology diffusion can be found in section 3.6.

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11 The application of ABS to computational economic modelling is generally known as agent-based computational economics (ACE) (Tesfatsion 2006, p. 835).

12 Klügl (2001, p. 102ff.) provides an overview of various existing simulation environments for ABS .

3.2.2.3 Integrated consideration of system dynamics and agent-based simulation

Observing the description of SD and ABS, it becomes clear that some similarities between both modelling approaches exist. Both are simulation models and can take into account dynamic changes over time as well as the perspective of individuals. However, each modelling approach tends to emphasise different properties. Whereas the SD methodology focuses on dynamic feed-back loops in a system, ABS concentrates on the perspective of individual agents. In line with a continuous evolution and improvement of existing modelling approaches, recent work in the field of simulation models has started to build a bridge between SD and ABS so as to combine the advantages (Duggan 2008). In this way various researchers integrate elements of both approaches in their modelling exercises. To cite one example, Schieritz & Großler (2003) argue that agent-based components can contribute to increasing the flexibility of a conventional SD model with a typically fixed stock and flow structure during simulation. An overview of developed examples combining SD and ABS is provided by Duggan (2008). In this context, basic ideas of SD such as dynamics and behavioural aspects may also be applied within integrated energy-economy-climate model, as realised e.g. by Fiddaman (2002).

3.3 Technology diffusion and technological change

3.3.1 Concepts of technology adoption and diffusion

Processes of technology adoption and diffusion in the energy sector are not exclusively driven by economic factors (Barreto & Kemp 2008; Grübler 1998, p. 91). Additional aspects and framework conditions determine whether a certain technology will be adopted in society and, if applicable, when the corresponding diffusion process takes place. In contrast to neoclassical economic approaches, market imperfections and uncertainty about technological evolutions are considered within technology diffusion research. The basic attempt to explain the deployment of new technologies in general involves the gradual adoption of new technologies by potential users, typically following a sigmoid course over time. In a survey paper about different models of technology diffusion, Geroski (2000) compares alternative explanations of why diffusion processes typically follow a sigmoid-shaped curve. To give an example, the lack of information is identified as the main factor slowing down the pace of technology diffusion in the epidemic model. In contrast, the probit model acts on the assumption that individuals or companies are characterised by different objectives, needs and abilities. According to Rogers (2003, p. 280ff.) one can distinguish between different types of adopters, whose behaviour principally determines the course of technology diffusion. Initially, the author assumes that the adoption rate follows a normal distributed function (see Figure 3-1).

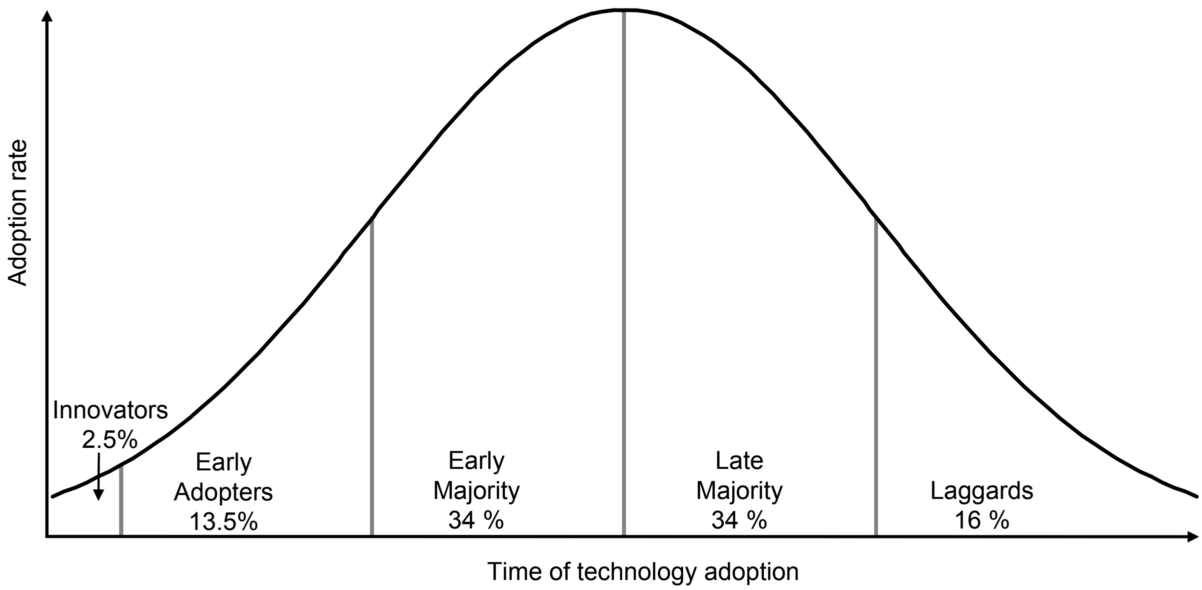

Figure 3-1 Categorisation of adopter types
Source: Based on the concept of Rogers (2003, p. 281)

The first group of adopters who accept a new technology are **innovators.** They are characterised as persons, open-minded towards new developments and willing to assume the potential corresponding risk. In addition, innovators are in funds to compensate unprofitable investments. Innovators rather stand for a marginal group in a social system, accounting for 2.5 % of the overall population. On the contrary, **early adopters** represent a larger group in society than innovators and assess thoroughly advantages and inconveniences of potential innovations previous to the adoption decision. Often, early adopters assume leadership roles in society and contribute to the distribution of information with regard to innovations. Pursuant to Rogers, early adopters constitute 13.5 % of the population. Then, Rogers (2003) differentiates between the **early majority** and the **late majority**. While the first group consists of persons acting deliberately but interested in innovations, neither belonging to the forerunner nor to the late adopters, the late majority is more sceptical towards innovations and just adopts in case of strong social push or economic necessities. Both groups represent 34 % of the overall population, respectively. **Laggards**, who can be characterised by a traditional and past-oriented attitude, are the last ones in adapting a new technology. This group stands for 16 % of the population. The described concept about the categorisation of adopters serves as a basis for the specification of agent-types for the model developed within this thesis (see section 5.4).

Over the past decade, a new research field dealing with socio-technical transitions of a societal system towards a more sustainable one has been evolving (Bergman et al. 2008). A transition can be understood as process of change leading to structural changes of a society (Rotmans et al. 2001). According to transition theory, the social groups of societal systems can be classified into socio-technical landscape, regimes and niches (Rotmans et al. 2001). The **socio-technical landscape** thereby defines the framework of a societal system including economic, political, environmental and social aspects at the macro level. Then, the **regime**, constituting practices, rules and shared assumptions at the meso level represent the dominant element of a system. It is mainly characterised by the objective to optimise a system instead of transforming it. Individual actors and technologies external to the regime are described as **niches** and can be attributed to the micro level. Activities and development on the niche market level as for instance in terms radical innovations might contribute considerably to transition processes (Bergman et al. 2008). Following the described concept of transition theory, it is suggested to consider the diffusion process of RET in the context of the transition of the energy sector towards a more sustainable energy system. Thus, RET can be attributed to the niche market level.

Likewise, Christensen (2000) differentiates between sustaining and disruptive technologies in order to explain the diffusion of emerging technologies from a company's perspective. Whilst technology innovation regarding sustaining technologies consists mainly in continuous improvements of well established products, disruptive technologies rather describe radical innovations. In addition, the author intends to explain failures of companies as their inability to cope with disruptive technologies (Christensen 2000). Following this definition one can characterise RET as a kind of disruptive technologies that emerge within the energy system, which is still characterised by a dominance of well established conventional conversion technologies.

Moving away from the general description of technology diffusion aspects, their relevance for the energy sector is put forth subsequently.

3.3.2 Technology adoption and diffusion in the energy sector

In a first example Grübler et al (1999) pinpoint the necessity to consider aspects of technological change within models dealing with environmental issues in general with a focus on energy technologies. One main reason is the long-term time scale, which is a typical timeframe for changes in the energy system due to the long lifetime of the associated energy conversion technologies. Consequently, the authors suggest the inclusion of S-shaped diffusion patterns and learning phenomena into models applied to analyse patterns of environmental change[13]. According to the authors, concerns about global warming contribute to the creation of niche markets for low-carbon technologies, such as RET. To a certain extent, one can consider the current status of most RET as a kind of niche market commercialisation. Existing national support schemes and the associated financial incentives have been contributing to creating this niche market for RET. Likewise, Barreto & Kemp (2008) suggest a better integration of technology diffusion aspects into energy system models including the impact of spatial technology spillovers. They also identify patterns in research and development as important drivers for technological development.

In another piece of work, Jacobsson & Johnson (2000) propose to study the diffusion of RET from an innovation system perspective. This suggestion is motivated by the fact, that the diffusion of RET represents a core element of a currently emerging transformation process in the energy sector towards a more environmental-friendly energy system. Thereby, emerging RET replace or complement existing conventional energy conversion technologies, which are predominantly part of the incumbent actors in the energy system. The authors highlight the role of networks, institutional aspects and the existence of prime

13 A more detailed description how learning phenomena are dealt with in energy models is provided in section 3.3.3.

movers for the diffusion process of RET. Similarly, Tsoutsos & Stamboulis (2005) identify the diffusion of RET as a technological regime shift and stress the importance of integrating the innovation dimension into the design of policies aiming on the support of niche market technologies, or RET in this case. Switching over to qualitative analysis applied to concrete examples, there is some work available analysing RET in the context of the British innovation system (Foxon et al. 2005; Foxon & Pearson 2007). Eikeland & Süverud (2007) make an attempt to categorise exemplarily European countries according to the different types of adopters with a focus on market support policies for RET. To mention one example of dealing with technology diffusion in a quantitative manner, the reader is referred to the work of Söderholm & Klaassen (2007), who analyse innovation and diffusion of wind power by means of an econometric model.

In order to analyse long-term developments in the energy sector, as the diffusion of RET, the existing technology diffusion literature provides the basis for the characterisation of the given problem including the identification of the relevant drivers in a diffusion process. In addition, the categorisation of adopter types helps to identify potential agent characteristics, which can be used within the developed model. However, most of the presented work represents rather conceptual and qualitative work or focuses on a stylised representation of technology diffusion patterns.

3.3.3 Including technological change in energy models

Since the technological performance of energy conversion technologies and its development over time significantly determines technology costs, it is generally considered to be an important factor in energy models. In earlier applications cost reductions have been incorporated into energy models exogenously, assuming that costs decrease as a function of time. However, cost reductions do not only depend on the course of time, but also on the accumulation of experience available with a certain technology (Uyterlinde et al. 2007). Energy modellers have started to internalise the process of technological change to take into consideration the fact that changes in the technological performance depend on whether a technology is employed or not (Grübler et al. 1999; cf. Messner 1997). Several effects such as learning-by-doing, learning-by-using, learning-by-interacting, mass production and up-scaling are assumed to cause a decrease in production costs with increasing cumulative experience, e.g. measured in terms of capacity. In quantitative terms, each doubling of cumulative capacity or production involves a constant percentage of cost reduction, expressed by the learning rate.

The impact of cumulated R&D expenditures on production costs or the learning-by-researching effect has been identified as one important additional learning mechanism to further improve the concept of the standard experience curve or the one-factor learning curve. Consequently, researchers have amplified the one-factor learning curve by learning-by-researching effects to the two-factor learning curve. Typically technologies which are still in their invention stage are characterised by higher learning-by-researching rates than more mature technologies. Barreto & Kypreos (2004), Miketa & Schrattenholzer (2004) and Kouvaritakis et al. (2000) show examples of how the two-factor learning curve can be incorporated in energy models.

However, the practical implementation of technological learning in energy models using a linear programming approach involves some problems associated to the non-linearity and the non-convexity of learning curves (Kahouli-Brahmi 2008). By introducing endogenous technological learning these models are converted to a non-linear problem, which can no longer be solved by standard optimisation algorithms. Instead, mixed integer programming or iterative solutions may be applied to solve the modified non-linear and non-convex programs leading to an increase in computation time.

According to Schumacher et al. (2007) the implementation of learning curves in energy models depends on the model structure. Whilst energy system models analyse the impact of learning effects on investments in power plants and the involved capacity development, macroeconomic models analyse price and demand effects caused by learning phenomena.

Despite the abundant work available about including technological learning in energy models, there are still several weaknesses related to the concept of the experience curve. These include the uncertainty of empirical learning rate parameters and the omitted variable bias (cf. Kahouli-Brahmi 2008). The latter is caused by factors that exercise influence on production costs – e.g. changes in input prices – but which are not separately considered in the learning curve. Schumacher et al. (2007) identified the system boundaries – specifying whether learning takes place globally or on national level – as an issue that still needs to be addressed. Furthermore, the availability of cost data has proved to be a problem, as predominantly only prices, which do not necessarily reflect production costs, are available (cf. Schumacher et al. 2007).

3.4 Suitability of modelling approaches

Based on the described existing approaches for modelling the energy sector the rationale for choosing a certain modelling approach are exposed. Keeping in mind the aforementioned criteria (see section 3.1) of the ability to represent accurately the techno-economic characteristics of RET, top-down approaches are not considered an appropriate tool for the given problem. Hence, the application of a bottom-up model results to be suitable to analyse the future development of RET.

Next, a decision between the application of an optimising energy model and a simulation approach is made. Therefore, the varying objectives pursued by both modelling approaches represent a contributing factor for the decision. Whereas simulation approaches usually are applied to evaluate the consequences of existing options for action, optimising energy models aim at identifying the cost-efficient option (Enzensberger 2003). In addition, the diffusion of RET in reality is not predominantly a result of a central planning process, but rather a result of the combination of numerous individual investment decisions. The adoption and diffusion of new technologies in the real world might be hampered by several factors including a failure of markets, networks and institutions (Jacobsson & Johnson 2000, p. 631). According to Jacobsson & Johnson (2000) these inhibiting factors may include incumbent market participants exercising market power, insufficient knowledge networks or legislative failures favouring the well-established technologies. Therefore, the negligence of optimisation models to consider market imperfections, as described by Zhang & Folmer (1998, p. 105), strengthens the argument to select a simulation model for the given problem. As a last criterion, simulation models tend to allow for a higher flexibility required in order to represent the continuously changing framework conditions.

The aforementioned arguments support the selection either of a SD approach or ABS modelling concept for the given question. This pre-selection is affirmed if the market diffusion process of RET and the corresponding replacement of fossil fuel based conversion technologies is regarded as a transition process towards a more sustainable energy system following the concept of transition theory. In transition theory, the technology innovation and diffusion process is described as a structural change of a societal system (Rotmans et al. 2001). Bergmann et al. (2008) suggest using a combination of agent-based modelling and SD thinking to assess the transition of a societal system.

Finally, a decision between the application of a SD model or an ABS approach has to be taken. If the given question rather focuses on the analysis of social interactions and processes leading to a certain development, Janssen (2004, p. 157) recommends to apply ABS models instead of equation-based models like SD. In contrast, the SD approach focuses more on the existing interactions between system components than on aspects of individual behaviour. With regard to the diffusion process of RET the heterogeneous motivation of potential investors in the respective market including non-economic reasons, such as ecological motivations, plays a decisive role. Dawid (2006, p. 1255) judges heterogeneous behaviour of agents to be one crucial attribute of many economic processes, in particular if innovative activities are part of it . Due to this prominent role of individual behaviour and individual decision making for processes of innovation and technological change the agent-based approach is evaluated to be the appropriate approach for analysing the diffusion of RET in the electricity market.

Examining the technical perspective, an object-oriented modelling environment, frequently used in combination with multi-agent-models, is favoured over the use of commercially available software tools for SD (e.g. VENSIM, POWERSIM) due to its high level of flexibility. The basic concept of object-oriented programming languages is well suited for a representation of agent characteristics, including its modular design and the autonomy of objects. It is supposed that the characteristics of agent-based modelling offer a broader perspective for future model developments including e.g. the learning component of agents. Indeed, both modelling approaches still appear to be capable of coping well with the requirements listed in section 3.1. For further examples comparing and combining System Dynamics and Agent-based modelling the author refers to (Bergman et al. 2008; Schieritz & Großler 2003; Wakeland et al. 2004).

As proposed by Rosen (2008, p. 218), the ABS modelling approach is combined via soft-link with a geographical information system (GIS) in order to apply for the heterogeneous resource availability of RES. Geographically explicit resource-curves are derived exemplarily for the case of onshore wind and solar PV.

Figure 3-2 summarises the core requirements for the selection of the modelling approach graphically.

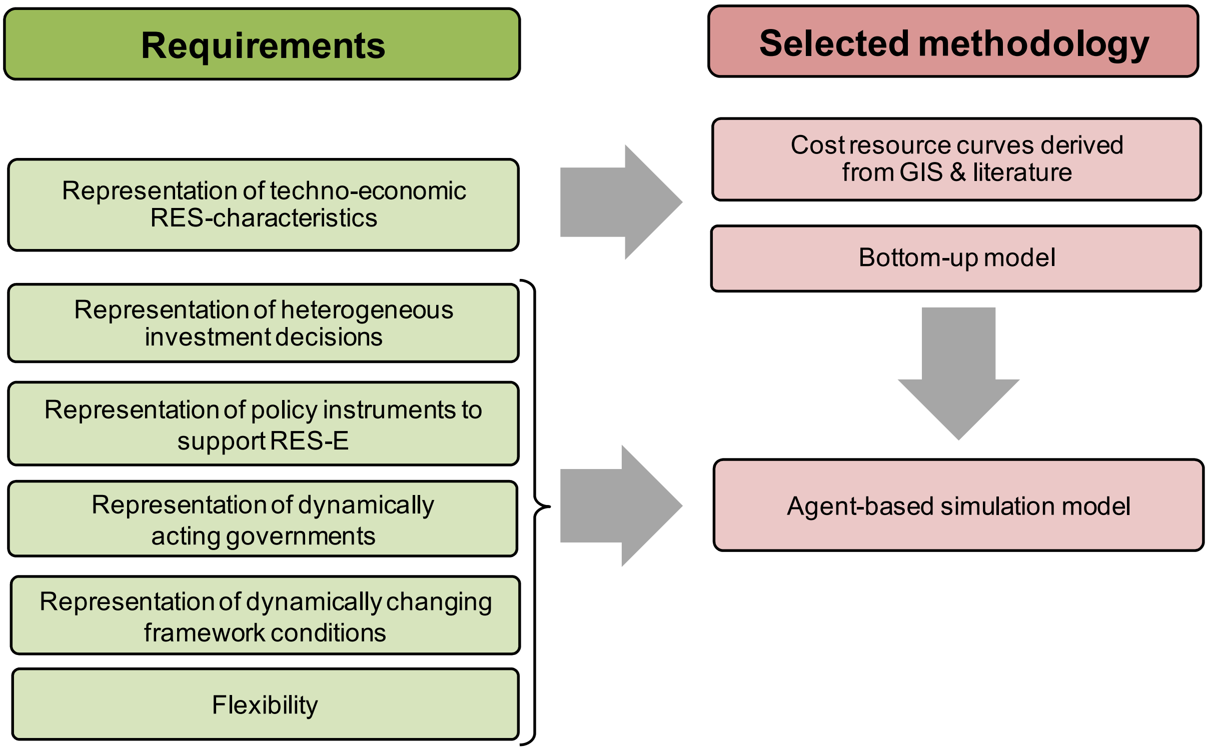

Figure 3-2 Overview on the requirements for the methodology and the corresponding selected methodological approaches

Source: Own illustration

3.5 Examples for considering renewable energy sources in energy models

Moving over to concrete examples of how to deal with problems regarding RET, four different categories are distinguished. The first category deals with the consideration of RET as part of the whole energy system within optimising energy models. As the modelling of RET requires an extensive knowledge about the available resource potential, the corresponding conversion technologies and the economic characteristics, various models have been developed in the context of increasing relevance of RET in recent years. Thus, the second category presents some examples of model applications focussing on the detailed representation of RET. Thirdly, examples of integrating uncertainty into the modelling of RET are described. Since the diffusion of RET depends inter alia on the successful integration of RET into the existing infrastructure, the implications of operational aspects on the diffusion of RES are shortly discussed in the forth category.

3.5.1 Renewable energy sources in optimising energy models

In the past, many applications of optimising energy models tended to disregard the role of RET owing to the low market share of RET and their consequential low influence on the overall energy system. The development of RET did generally not represent the object of investigation itself, but was rather integrated into the models in terms of predefined market development scenarios as an additional modelling constraint. However, the relevance of RET on the energy system as a whole has been augmenting with an increasing share of RES in energy supply during the last decade. Therewith, a stronger consideration of RES development within optimising energy models is necessitated. This section presents some exemplary applications of optimising energy models attaching special importance to RET.

Remme (2006) makes an attempt to integrate RET into the linear programming based energy system model TIMES[14]. The presented model covers the German electricity sector up to the year 2050 and focuses on sensitivity analysis and parametric programming. The techno-economic characterisation of the applied RET is based on the integration of cost-resource curves. The technological detail for some technologies appears to be on a highly aggregated level. With respect to onshore wind technologies, merely three classes of wind velocities are categorised (Remme 2006, p. 31). Learning effects and long-term developments of the specific technology investment are not modelled endogenously, but fed into the model exogenously. The author takes into account the fluctuating nature of wind and PV electricity by assuming the corresponding capacity credit to amount to 16 % of the total capacity of the respective technologies (Remme 2006, p. 158). With regard to the integration of the existing policy background in the area of RES, either minimum quantities for the future development of RES-E or an emission reduction scenario making RES-E compete with other emission reduction options, such as efficiency measures are assumed as active policy measures. Hence, the author focuses rather on the question about the consequences of an increased RES-E share and the possible contribution of RES to mitigating climate change. Thereby, he neglects the possible impact of currently applied technology-specific policies on EU-MS level. Commonly, FIT might be integrated into optimisation models with the objective to minimise costs by representing the financial support as negative costs. This means, that either the development of RES-E appears to be predefined in the first case and neglects existing technology-specific support options in the second case.

One of the first attempts to integrate the role of RES into a regional branch of the PERSEUS model family was made by Dreher (2001) in order to investigate the impact of environmental support schemes for RES in the German region of Baden-Württemberg. Rosen (2008) presents a further example of modelling RES within the PERSEUS model family. More precisely spoken he bases his work on the linear optimisation (programming) model PERSEUS covering the EU-Member States as of 2003 (EU15) and a time horizon up to 2020. It is thereby the main focus of the author to combine a long-term horizon capacity expansion planning with operational aspects of RES, in particular regarding the integration of fluctuating

14 A further applications of the TIMES model in the area of global climate policy is described by Remme & Blesl (2008).

wind electricity into the grid[15]. Static cost-resource curves, derived by Klobasa et al. (2004) for each RET, form the basis for the techno-economic characterisation of RES within PERSEUS-RES-E. The applied approach therewith disregards the potentially relevant impact of technological learning on the electricity generation costs of RES. As opposed to the application of Remme (2006), the author incorporates the available financial support at national level into the model. As the applied cost-minimising approach does not consider revenues, available revenues from RES-support mechanisms such as feed-in tariffs are transformed into negative costs[16]. In case of quantity-based support mechanisms (quota obligation with TGC, tender procedures) the target is implemented in terms of an additional constraint. However, the underlying assumption, that the quota will be fulfilled in each given period is not always concordant with the real situation. To give an example, Belgium, Sweden and the UK did not fulfil the predetermined quota targets every year considering the period from 2002 to 2005 (Ragwitz et al. 2007, p. 132 – 135). With respect to the diffusion process of new technologies within optimising models, the author reports on a certain kind of bang-bang effect consisting in an overvaluation of the RES capacity growth if no additional diffusion restrictions are considered. However, the existence of factors such as available manufacturing capacities, permitting procedures or grid connection issues might determine the future development of RES. Therefore, the author implements an additional annual construction constraint and an upper limit for the overall electricity generated with RES and analyses their impacts on the RES-development. It is important to notice that the quantification of these growth restrictions represents a rather challenging task. In this case electricity generation limits are assumed to be below 1.5 times the linear interpolated increase between electricity generation in 2002 and the realisable potential by 2020. Even though modelling results indicate lower theoretical policy costs in case of quota obligation systems, the author recognises that transaction costs and higher investment risks might influence considerably on the performance of this support scheme in practice. One further application example of the PERSEUS model analyses the interactions between the development of RET in the electricity sector and emission trading (Möst & Fichtner 2010).

Karlsson & Meibom (2008) analyse future investment pathways of RET and hydrogen technologies in the overall energy sector including heat and transport for Scandinavian countries. For this purpose, the linear optimising energy model BALMOREL is applied. The technological detail used within this model shows a rather high aggregation level and does not report on dynamic changes of the economic characteristics of RET over time.

Summing up, all presented approaches integrated RET options into optimising energy models with different focuses and accuracy levels regarding the representation of RET options. All the described applications distinguish themselves by their capability to cope with possible interactions between RET and the rest of the energy system. At the same time the systemic perspective of the models tends to involve a low

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15 Aspects of power production planning with a focus of the integration of wind into the electricity system are analysed exemplarily for Spain and Germany.

16 There are some approaches of integrating profit maximisation practices into linear optimisation models, e.g as applied by Göbelt (2001).

level of detail regarding the techno-economic characterisation of RET. The regional aspect of cost-resources curves is not considered in neither of the presented models. None of them integrates the actor's perspective into the modelling exercises. Observing the example of Rosen (2008) it becomes evident that it is indeed possible to integrate the impacts of policy instruments on the trajectory of RET in terms of negative costs. Nevertheless, the fixed structure of optimisation models tends to complicate a flexible implementation of various policy designs.

3.5.2 Models focussing on technologies using renewable energy sources

As the description of the various RES characteristics requires a high level of detail (see section 3.1), some models focus on the analysis of the renewable energy sector without modelling explicitly developments in the conventional energy sector. Developments in the energy system relevant for the use of RES (e.g. electricity demand, electricity prices) are rather considered as a set of framework conditions and are often included within the modelling exercise in terms of exogenous inputs.

One example for modelling the renewable energy sector is the dynamic market simulation model ADMIRE-REBUS. The fundamentals of ADMIRE-REBUS were established by REBUS, a static model applied in order to simulate the effects of a TGC system in the EU15 up to the year 2010 (Voogt & Uyterlinde 2006). Basically, the model calculates the equilibrium TGC price corresponding to the marginal costs of the most expensive technology option required to fulfil the predetermined target. ADMIRE-REBUS integrates technological developments and amplifies the geographical horizon to the EU25 as well as the time horizon to 2020 (Uyterlinde et al. 2007). In contrast to the first model version, ADMIRE-REBUS incorporates profitability considerations of investors besides cost aspects and distinguishes between country- and technology-specific profitability expectations. An additional cost factor is taken into consideration to apply for the fluctuating power output of some RES. The model is able to analyse biomass imports, as described in detail by Skytte (2006).

A case in point for modelling the renewable energy sector in a detailed way is the model cluster developed by the University of Vienna. Initially, the partial equilibrium model ElGreen was designed in order to analyse the impact of various support schemes on the technology diffusion and adoption of RET. Static cost-resource curves represent the core principle of the modelling approach used within ElGreen (Huber et al. 2004). Drawing on this concept, dynamic aspects have been integrated into an amplification of ElGreen, the Green-X model (Resch et al. 2004; Resch 2005). The model developers take into account aspects of technology diffusion resulting from non-economic diffusion barriers. The outstanding characteristics of the Green-X-model consist in the high level of detail regarding the dynamic cost-resource curves and in the explicit modelling of different policy approaches. In general, the model covers the electricity, heating and the transport sector. In its recent version, the model developers made an attempt to take into account the possible competition for biomass feed-stocks in all three sectors (Ragwitz & Resch 2006). The Green-X model does not rely on cost-resources curves from literature, but uses own derivations of cost-resource-curves. Regarding interactions with the conventional energy system, there is an extended version of Green-X covering the EU15, which endogenously models conventional electricity generation options in a simplified way (Ragwitz & Resch 2006). However, exact implementation details do not become clear. Another model branch developed by the same research group is the GreenNet model with a focus on grid integration issues of fluctuating RES (Auer et al. 2006).

Recapitulating, both presented examples model the development of RET explicitly. In particular the modellers from the University of Vienna put emphasis on the derivation of detailed cost-resource curves for RET. However, neither of the models uses cost-resources curves that are based on geographical information or considers the actor's perspective.

3.5.3 Models integrating uncertainty aspects

Investment decisions in the energy sector are subject to the uncertain development of some relevant input parameters, as for instance electricity prices or demand developments. Accordingly, there are modelling approaches aiming at the integration of uncertainty[17].

In this way, Madlener et al. (2005) integrate stochastic elements into an optimisation model representing technology adoption processes of energy technologies in the Turkish electricity sector between 1970 and 2000. The authors base their research on the maximisation of the expected net present value. In contrast to deterministic profit maximisation approaches, the timing of the investment and the subsequent plant construction plays an important role for profitability considerations within the real-options approach applied in this paper. This means, that a potential investment might be realised in each year of the considered time horizon involving differing profitabilities. Demand of peak load capacity, unit generation costs and electricity prices are modelled in terms of stochastic ARMA-processes[18]. However, RET do not play a central role within this analysis. In contrast, Kumbaroglu et al. (2008) modify the described model addressing the development of the Turkish electricity system from a prospective perspective up to 2025 with a focus on RET. The dynamic technology adoption sequential decision model was developed from the beforehand described linear programming approach. Further, the authors integrate information on technological learning, construction lead times, time-variant price elasticities and non-stationary stochastic processes into their model. However, the level of detail regarding the techno-economic description of RET based on MARKAL-MATTER data appears to be comparatively low including e.g. only one single capacity factor in the case of wind energy (Kumbaroglu et al. 2008, p. 1896). Similar to the application of Rosen (2008), artificial maximum growth rates for RET are assumed in order to apply for the existence of non-economic barriers. Within the scenario calculations, the impact of predefined targets is addressed without considering possible implications of price-based policy schemes.

Further applications of how to deal with uncertainties in the electricity sector in the context of climate policy are exposed by Fuss et al. (2008) and Fuss et al. (2009). However, it should be noted that the cor-

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17 Walker et al. (2003) provide a conceptual basis for managing uncertainty within modelling and understand uncertainty as *"any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system"*.

18 ARMA processes (Auto-Regressive Moving Average) are linear models for the representation of statistical processes. For a more detailed description of advanced statistical processes, please see Weber (2005, p. 45ff.).

responding technological detail of the presented examples remains on a rather aggregated level including two to three representative technology types.

3.5.4 Integrating renewable energy sources in the electricity system

The fluctuating nature of some RES, such as wind or PV, poses an important challenge for system integration issues. In literature, a number of approaches dealing with operational aspects of RES can be found. Some selected studies are presented exemplarily in this section in order to provide some insights into this problem and to point out potential cost implications on the future development of RES. As the modelling of operational aspects of RES integration goes beyond the scope of the thesis at hand, this section describes rather results obtained within the models than the modelling approaches themselves.

As already described in section 3.5.1 the model described by Rosen (2008) analyses short-term effects of wind integration into the system in combination with a long-term investment planning module without considering the option of grid reinforcements and extensions. Thereby, the author quantifies the reserve capacity required in order to compensate for the comparatively low capacity credit of wind technologies. The capacity credit or the secured capacity of wind power describes the amount of conventional power capacity that might be substituted by wind power plants. Due to the lower availability of the rated power and the fluctuating nature of the electricity output, an increasing penetration of wind power requires additional secured capacity, which might be provided e.g. by gas-fired power plants.[19] Results indicate a required reserve capacity in the order of 50 GW for the EU15 corresponding to a scenario with 1.160 TWh of renewable electricity generation by 2020. The corresponding specific additional costs per unit of renewable electricity range from 0.13 € Cent/kWh in Germany to 0.67 € Cent/kWh in Spain (Rosen 2008, p. 198). Then, the author investigates the impact of an increased number of start-up and shut-down procedures of conventional power plants, necessitated to cope with the fluctuating feed-in of wind power, exemplarily for Germany and Spain. The resulting efficiency losses implicate costs below 0.25 € Cent per kWh of wind electricity. Findings from this study indicate that costs induced by the fluctuating nature of wind energy are significantly lower than the actual electricity generation costs.

Auer et al. (2006) investigate the costs of RES integration into the electricity system by means of the GreenNet model, assuming a continuous mathematical function between the share of wind energy and the associated grid extension and reinforcement costs. According to the authors, a wind penetration of 30 % involves grid-related specific costs in a range of 0.4 to 0.6 € Cent /kWh.

According to a paper published by Swider et al. (2008), grid connection costs in selected countries, identified in several case studies, range between 35 and 210 €/kW for onshore wind depending on various influencing factors. The respective costs for offshore wind power plants are in the order of 180 – 600 €/kW representing thus a considerable share of the total investment.

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19 Voorspools & Dhaeseleer (2006) propose an analytical formula for the calculation of the capacity credit of wind power.

As reported by Gül & Stenzel (2006), further options of how to manage the integration of fluctuating generation into the electricity system in addition to the provision of capacity reserves and grid-related actions are the storage of electricity or demand side measures. Storage technologies include pumped-storage hydropower plants, hydro reservoirs, compressed air storage, flywheels or batteries, but only pumped-storage hydropower plants or hydro reservoirs are broadly used on a commercial level at present (Gül & Stenzel 2006). One example for the analysis of demand side measures in order to facilitate system integration of wind energy into the German electricity system is provided by Klobasa (2007). A similar study with a focus on the Northern European electricity market was realised by Holttinen (2004).

The investigated studies show that it is essential to take into account operational aspects of integrating RES-E in the electricity system in the context of a long-term trajectory. However, results from the analysed papers indicate that additional costs of system management caused by the fluctuating character of the electricity output remain on a manageable level. Taking into account additional options of electricity storage and reinforcement of interconnection capacities, it appears that operational problems can be resolved in the long-term. In combination with reinforcing the existing electricity network and the use of distributed storage in terms of electric or hybrid vehicles, these measures may contribute to managing the integration of a considerable share of fluctuating RES-E.

3.6 Examples for agent-based simulation of technology diffusion

Most existing ABS approaches in practice focus on problems regarding a short-term or a medium term time horizon. However, recent developments show an increasing number of examples, where the concept of ABS has been applied for the analysis of long-term developments. According to Dawid (2006) ABS seems to be better suited for the representation of innovation and diffusion patterns than neoclassical equilibrium analysis. The author judges ABS to be a principally powerful approach for analysing aspects of technological change due to its ability to integrate well some specific features of innovation processes. In this way Dawid (2006) presents and discusses various implementation examples of ABS in the field of innovation and technological change. At the same time he admits that some aspects of the process of technological change are still predominantly integrated into modelling exercises in a highly stylised manner.

Janssen (2004) identifies ABS as one promising approach to tackle problems in the context of ecological economic systems including its application to diffusion processes. As a core motivation for the use of ABS the author mentions the analysis of processes and social interactions on micro level and their implications for macro-phenomena. Nevertheless, applications for modelling technology diffusion processes based on the concept of ABS in the energy sector are still scarce. However, there are approaches of how to simulate the diffusion process of emerging technologies by means of ABS in other areas. These examples are shortly summarised within this section as they provide insights into the modelling procedure. Some of the basic ideas might be applied to the diffusion process of RET. This section's objective is to provide an overview of recent work existing in the field of ABS with a focus on technology diffusion patterns.

3.6.1 Stylised agent-based simulation approaches

Some basic ideas for modelling the diffusion of RET are provided by some stylised examples of how to represent technological innovation by means of ABS. The work carried out by Ma & Nakamori (2005) simulates a technological innovation process by means of a multi-agent model, assuming that technological innovation can be regarded as a kind of evolutionary process. It is the objective to analyse rather the consequences of interactions and assumptions than to provide a forecast tool for a specific type of innovation. The model, developed on the basis of an object-oriented programming approach, simulates various fictive situations, where the interaction of producers and consumers determines the technological innovation process. Different degrees of information availability and three evaluation methods applied by the consumers represent the core agents' characteristics of the developed model. The authors judge ABS to be a useful tool in order to obtain insights into the process of technological change.

In a more recent piece of work, both authors combine the concept of ABS with an optimising modelling approach under uncertainty in order to build a stylised model of technology adoption in the context of sustainable development (Ma et al. 2009). Decreasing costs as a consequence of technological learning represent a further relevant driving force of technology adoption considered within the developed model. Two particular types of decision makers are assumed according to their risk attitude. In terms of diffusion theory, one risk-averse agent thereby represents a follower, whereas the risk-taking agent stands for a first mover. Three technologies, which are characterised according to their market maturity as existing, incremental or revolutionary technology, constitute available alternatives for the agents' decisions. Uncertainty is considered by the integration of uncertain carbon taxes (assumed to be Weibull-distributed) and learning rates (assumed to be lognormal-distributed). Additional aspects that have been considered by the authors are technological spillovers and trade in resources and goods. Despite the stylised character of the developed model, some interesting conclusions for a better understanding of the technology diffusion process can be drawn. Among other findings the uncertain future technological learning appears to delay investments into research and development as compared to a case without considering uncertainty. In contrast to the common opinion technological spillovers even might hamper the application of advanced technologies.

Another piece of research, described by Bergmann et al. (2008), deals with the modelling of socio-technical transitions from an agent-based perspective. The researchers model three functional levels, referring to niches, empowered niches and regimes in terms of aggregated complex agents, as well as consumer agents that support a specific type of a complex agent. Specified activities or practices are attributed to the complex agents together with further characteristics including the support from consumer agents and strength. Strength in turn expresses the agent’s ability to influence the society or other agents. In principle, regimes are considered to be stronger than empowered niches and empowered niches are in turn stronger than niches. External signals are used to represent the influence of the socio-technical landscape. Within the developed model a transition might occur either through the change of a regime, if the established regime becomes too weak and another regime evolves or by an evolution of the existing regime. Interactive mechanisms between the agents represent a further key element of the model developed. In this way, agents might adapt modified practices, new niches might appear and niches might be absorbed or build clusters. Further, a transformation of an agent type to another is allowed according to its dynamic strength. The developed model provides important insights of how to represent a transition process using ABS. However, the researchers still report on different degrees of success in their attempt to reproduce historic examples of transition processes and the difficulty to calibrate the model. The model is adapted to several case studies including its application to a transition of the European transport sector (Köhler et al. 2009). One further application of ABS in the context of transitions to a sustainable economy is provided by Safarzynska (2009). The author analyses technology lock-in situations considering the coevolution of demand and supply under increasing returns (cf. Safarzynska & van den Bergh 2010) and applies a model based on heterogeneous boundedly rational agents to simulate a transition to a low carbon energy system in a stylised way (Safarzynska 2009, p. 111-127).

The described modelling approaches contribute considerably to the explanation of technology diffusion processes in general and identify important basic coherences in this context.

3.6.2 Agent-based simulation in the energy sector

Original applications of ABS to problems in the electricity sector available in literature mainly focus on operational aspects than on the analysis of long-term developments[20]. However, a number of concepts has been developed in order to analyse problems of long-term planning in the energy sector based on agent-based approaches in recent years. In general, the capacity development of energy conversion technologies resulting from individual investment decisions represents the core element of the approaches described subsequently. Following this reasoning, Fichtner et al. (2003) suggest a combined application of an agent-based approach and a linear optimisation model for strategic planning patterns of electricity suppliers in liberalised markets. The authors pinpoint the ability of agent-based approaches to represent adaptive market actors with heterogeneous behaviour and objectives, allowing therewith for a more realistic representation of the actual situation. In addition, the modular configuration is quoted as a further advantage of the ABS approach. Another piece of work, carried out by Czernohous et al. (2003) includes a regulatory agent into an investment planning model based on a hybrid modelling approach that combines ABS with linear programming. Short-term decisions are still considered within this example. Although the authors judge agent-based modelling to be a potentially powerful concept for decision making support in the electricity sector, they characterise the realistic representation and calibration of individual behaviour as a challenging task.

Botterud et al. (2007) amplify the existing agent-based EMCAS-model[21], originally developed in order to realise short-term simulations, by long-term aspects. The authors decided to use an agent-based modelling concept to explore generation expansion processes of generation companies in liberalised electricity mar-

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20 For a comparison of ABS approaches applied also for the investigation of short- and medium aspects, the reader is referred to Sensfuss et al. (2007). Weidlich & Veit (2008) provide a compilation about agent-based wholesale electricity market models.

21 For a description of the EMCAS-model please see Veselka et al. (2002).

kets. ABS allows them to consider the existence of competition between generation companies, market power, limited information and further characteristics of liberalised electricity markets. According to the authors, these characteristics, which are usually not considered within traditional least-cost planning approaches, represent relevant driving forces for capacity expansion decisions. The presented model still includes the operational aspects. Uncertainties in the development of load, hydropower availability and the competitors' investment decisions are taken into account by means of scenario trees. One interesting aspect of this work is how investment decisions of the generating companies are modelled. They are based on multi-attribute utility theory (MAUT)[22], focussing on three attributes, including the discounted profit, the profit ratio and the market share. Individual risk preferences are also considered. Each generation company that is represented as an agent, forecasts the future market conditions and anticipates their competitor's decision. Looking at the role of RET, one should consider that capacity decisions in the field of RET are dealt with in terms of exogenous inputs. The developed model is applied to a real-world example reflecting the power system in South Korea. It should be noted, that the possible solution is reduced by allowing the construction of only one plant per time frame. All in all, the developed approach shows an example of how to apply ABS to capacity expansion planning in the electricity sector and provides important insights into specific issues of market design.

Some further work in this field was carried out by Wittmann (2008). He developed an agent-based model of energy investment decisions in urban energy systems with a focus on decentralised technologies. Motivated by the challenge to represent a technically complex system on the one hand and decentralised decision-making processes on the other hand, the author decided to combine an energy system model with ABS element. Regarding the structure of the model, the author distinguishes between a technical dimension, represented by an energy system model[23] and the agents' dimension, represented by an agent-based model. The main interacting agent groups are private actors on the one hand and commercial actors on the other hand. While private actors base their decisions on bounded rational decisions, the commercial actors use a rational choice model integrating various perspectives.

Going more into detail regarding the design of the private actor model, the actors are subdivided into technology leaders, traditionalists and established agents, following the SINUS-Milieu-Topology[24]. In addition, the author assigns varying rationality types to the model agents determining again the corresponding search rule of the decision heuristics applied. Finally, a combination of both features determines the agent types. The author mentions, that the agents’ specification is realised based on expert judgement and not based on empirical data. The actual decision procedure made by the agents consists of an information gathering procedure including the application of several search rules, an analysis tool in order to

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22 The applied additive MAUT consists in a combination of individual utility functions, where the total utility is the weighted sum of single attribute utilities. For a more detailed description of the theoretical concept of MAUT, please see Keeney et al. (2003).

23 The linear optimisation model deeco is used for this purpose. More information about this model is available at http://www.iet.tu-berlin.de/deeco.

24 For a description of the SINUS-Milieus, the reader is referred to http://www.sociovision.com.

calculate the key metrics to measure target achievement and their strategic evaluation through various decision strategies. At the same time, budgetary constraints and minimum requirements have to be fulfilled. Finally, a decision matrix combining the described elements is developed. With regard to the targets persecuted by the agents of the analysis tool, multiple decision criteria are assumed. As key figures for the description of economic criteria the author uses investment, operational costs, the payback time or the net present value, depending on the rationality type of the corresponding agent. In case of environmental criteria, a qualitative ranking of the given technology alternatives represents one criterion, whereas the cumulated energy consumption and the CO_2 emissions of each technology option are used as quantitative indicators. The last agents' objective of living comfort is specified in a qualitative manner. Albeit the author still recognises the need for further research regarding the empirical foundation of agent-types and the specification of weight factors within the decision analysis, he manages to display a diffusion process by means of agent-based simulation arising from the different agents' behaviour. For instance, technology leaders might adopt an emerging technology despite it is not yet profitable, whilst traditional agents smoothen the phase-out of an obsolete technology as they still stick to the traditional option.

The commercial actor model builds on heterogeneous prototypes of energy companies that consist of different business units and pursue different commercial strategies. More concretely, the author differentiates between an incumbent utility focussing on the use of centralised energy conversion technologies and a new market entrant with a comparatively low capital structure and with a focus on decentralised generation options. Investment decisions are taken at an operational, low-stake structural and a high-stake structural level. Whereas criteria in case of operational and low-stake structural decisions are calculated endogenously with the energy system model deeco high-stake decisions are predetermined exogenously.

Concluding, the developed model tackles problems in urban energy systems from a new perspective, enabled by an ABS approach. Interactions are explicitly modelled and in particular the private actor model of Wittmann (2008) provides important insights of how to model different agent types according to their innovation friendliness. At the same time the model in its current status remains on a prototype level and cannot be applied for the assessment of problems in the real world. This fact can be explained by the generally observed difficulty of agent-based models to parameterise data to real world conditions. Any kind of learning process of the involved agents is not dealt with in this model. In general, the developed model focuses on the representation of consumers and producers, whereas any kind of governmental interactions is not modelled endogenously.

To give an example for modelling the diffusion of RET by means of ABS, the work of Madlener & Schmid (2009) is exposed. The authors analyse the spatial diffusion of agricultural biogas technology in Switzerland by 2025 combining ABS with a GIS. In doing so, the GIS provides the data input in terms of available resource potential on community level. With regard to the agents' structure, several different agent classes are developed. Agents are supposed to act in the following way. The investment decision maker calculates the potential revenue of an investment into biogas technologies considering various inputs provided by various other agents including financial support conditions provided by a government agent and the potential resource availability and costs provided by the virtual substrate supplier agent. In addition, the techno-economic plant characterisation is made available by a plant manufacturer. Depending on the diffusion stage as described by Rogers (2003), changing minimum profitability requirements are assumed in order to apply for higher risks in early diffusion stages. A further stylised fact of diffusion processes is integrated in terms of adoption rates ranging from 10 to 25 %. Technological change is not considered within this application. In contrast to the model developed by Wittmann (2008), this example is applied to a specific problem in the real world. However, the application of three technology classes and one substrate type still indicates a considerably high level of abstraction.

Further, the ABS tool PowerACE market was developed in order to analyse the German electricity market focussing thereby on three main topics. First, Sensfuss (2008) and Sensfuss et al. (2008) analyse the impact of renewable electricity generation on the electricity market. One part of the developed model addresses the expansion of onshore wind energy in Germany in a first approach and serves as a basis for the model development realised within the thesis at hand. Another branch of the model investigates the role of learning algorithms in price building mechanisms on the electricity market and the impact of market structure and design on electricity prices (Weidlich & Veit 2008). The third topic focuses more on long-term developments in terms of investment decisions in the conventional power sector (Genoese et al. 2007a) and on the analysis of market power (Möst & Genoese 2009).

Summarising, the examples presented deal with the capacity development of energy conversion technologies using an ABS approach. Investment decisions in conventional energy conversion technologies and in urban energy systems are subject of existing analysis. Another ABS analyses the diffusion process of biogas power plants including spatial information from a GIS with a focus on a small region (Switzerland).

3.6.3 Agent-based simulation in other sectors

In addition to ABS approaches in the energy sector, there are further examples of how to display technology diffusion processes in other sectors. Due to similar properties of the examples exposed in this section to the diffusion process of RET, some of the observed concepts provide important indications for the modelling exercise of the thesis at hand.

One of the earlier applications of ABS to problems of technology diffusion deals with adoption decisions of agricultural innovations by farms in Chile (Berger 2001). Various farm agents, differentiated according to the different adopter categories following the concept of Rogers (2003) pursue different objective functions. The applied decision rules are based on recursive linear programming procedures. The author includes geographical information in terms of cell-based data representation and considers interactions on a spatial level. However, technological change is not considered within this approach. In further developments, the author integrate the use of Monte Carlo modelling techniques for the creation of agent populations (Berger 2004; Berger & Schreinemachers 2006).

Schwarz (2007) and Schwarz & Ernst (2009) expose another application examining the diffusion of three water-saving innovations in a model region in Southern Germany. Agents represent different types of households according to lifestyles. Unlike most of the presented approaches, this model is calibrated against real data from an empirical survey realised in a small region in Southern Germany. Parts of the survey results then have been used to categorise adopter types following the concept of the SINUS-Milieus into post materialists, social leaders, traditionals, mainstream and hedonistic milieus. Based on the survey results, weights of decision factors - used within a multi-attribute utility function – are derived. Besides this deliberate decision function, a further decision rule based on a take-the best heuristic is applied in the model. Decision making processes of agents incorporate therewith aspects of bounded rationality and the theory of planned behaviour. Looking at the representation of the agents' interactions, an artificial social network, considering the spatial proximity of agents and their affinity to other lifestyles, is created. According to the authors, the network structure influences technological change process on global and local level. In order to avoid an escalating diffusion process, an artificial evaluation rate for decision makers is implemented. In this case, it represents the time interval of a decision, or more precisely corresponds to the reciprocal of the lifetime of a certain technology. A lifetime of 20 years therefore implicates a monthly evaluation rate of 0.4 %. This means that every agent replaces the respective technology once during a period of 20 years. The agent population within this model is assumed to be static. In their model development the authors did not take into account learning aspects. Summarising the presented modelling approach, the strength of this model represents the application of an empirical dataset for model calibration purposes. According to the authors, the developed modelling approach appears to be transferable to other sectors, as for instance to the diffusion of energy-saving innovations or the use of renewable technologies in households.

The introduced examples of applying agent-based modelling outside the energy sector to problems of technology diffusion have in common the breakdown of investing agents into different adopter types.

3.7 Summary and discussion

It was the objective of this chapter to select an appropriate modelling approach to simulate potential future development pathways for RET in the electricity sector. The requirements resulting from this purpose were derived in a first step. In order to facilitate this decision, the relevant modelling approaches that have been applied to similar problems in the energy sector, were exposed. Similarly, the main aspects of technology adoption and diffusion processes were described in order to apply for the long-term horizon of the given modelling problem. The decision on the modelling approach was taken in favour of the agent-based modelling approach, mainly because of its ability to represent individual investment decisions, its ability to integrate aspects of technology diffusion and dynamic political framework conditions, and its ability to represent techno-economic characteristics of RET explicitly. In particular with regard to the last criterion, the agent-based simulation (ABS) approach is complemented with geographically explicit cost-resource curves, to be derived for two technologies, using a geographical information system (GIS).

The second part of the chapter provided an overview of concrete modelling implementation examples. First, the role of RET in optimising energy models was discussed. Whereas these models appear to be well capable to cope with interactions between RET and the rest of the energy system, none of these models considers the regional aspect of cost-resource curves or the individual actor's perspective in an integrated way. The second category of models exposed focuses on a detailed representation of the techno-economic characteristics of RES without modelling the conventional technologies explicitly. In a further category, examples of how to integrate uncertainty in energy models were presented without considering RES-technology options in a detailed way. Then, models analysing the implications of operational aspects resulting from the fluctuating nature of some RES, such as wind or PV, were described. Additional costs of system management caused by the fluctuating character of the electricity output turned out to remain on a manageable level compared to total electricity generation costs of RET. A summary of the analysed modelling approaches is provided in Table 3-1.

Thereafter, different examples of how to represent aspects of technology diffusion in ABS models have been analysed. Some insights could be drawn from the examination of stylised ABS approaches such as the categorisation of investors according to different types of decision makers with different risk attitudes. Another example analysed the diffusion of niche market products into existing technology regimes by means of ABS. Looking at the existing agent-based models that simulate capacity expansion decisions in the energy sector and in other sectors, different characteristics of ABS have been applied. They include different search rules for agents to gather information, varying rationality types and the integration of spatial information in one case. The approaches exposed provide important insights into the possible treatment of RET in general and on how to model technology diffusion patterns from an agent-based perspective. Examples for ABS approaches of technology diffusion processes are recapitulated in Table 3-2.

Table 3-1 Examples for considering RET in energy models

Model category	Model name	Time horizon	Geographical coverage	Main focus	Source
RET in optimising energy models	TIMES	2050	Germany	Interdependencies of RES-E with the remaining electricity system using sensitivity analysis and a parametric programming approach	Remme (2006)
	PERSEUS-RES-E	2020	EU15	Short-term aspects of integrating RES-E into the electricity system	Rosen (2008) Möst & Fichtner (2010)
	BALMOREL	2050	Scandinavia	Future pathways of hydrogen and RET use	Karlsson & Meibom (2008)
Models focussing on RET	ADMIRE-REBUS	2020	EU15	Detailed cost-resource curves for RET and policy analysis	Parente et al. (2002) Uyterlinde et al. (2007) Voogt & Uyterlinde (2006)
	Green-X	2030	EU	Dynamic cost-resource curves for RET and policy analysis	Resch et al. (2004) Resch (2005) Ragwitz & Resch (2006)
Models integrating uncertainty aspects	-	2025	Turkey	Real option analysis of technology adoption processes of energy technologies	Kumbaroglu et al. (2008) Madlener et al. (2005)
	-	150 years	Stylised model. Not applied to specific geographic region	Uncertainties in the electricity sector in the context of climate policy	Fuss et al. (2009) Fuss et al. (2008)
Integrating RES-E in the electricity system	PERSEUS-RES-E	2020	EU15. Short-term aspects for Germany and Spain	Short-term aspects of integrating RES-E into the electricity system	Rosen (2008)
	GreenNet	2020	EU	Costs of RES-E integration into the electricity system	Auer et al. (2006)
	IWILAS	2020	Germany	Demand-side management options in order to integrate fluctuating electricity from wind energy	Klobasa (2007)
	EMPS, EFOM and SIVAEL	30 years	Scandinavia	Integration of large amounts of wind power in the Nordic electricity system	Holtinnen (2004)

Source: Own illustration

Recapitulating, no existing modelling approach, that covers the development of the most relevant RET in the electricity sector for a long-term horizon based on an agent-based concept and integrating spatially explicit cost-resource curves, could be identified. Consequently, an own model is developed in order to investigate the central question of this thesis. The next chapter reports on the derivation of cost-resource curves for RET – with a special focus on onshore wind energy – before the ABS model PowerACE-ResInvest is described in chapter 5.

Table 3-2 Examples for agent-based modelling of technology diffusion

Model category	Model name	Time horizon	Geographical coverage	Main focus	Source
Stylised agent-based simulation approaches	-	200 time steps	-	Technological innovation as an evolutionary process	Ma & Nakamori (2005)
	-	2300	-	Technological change in energy systems under uncertainty. Based on two agents with different risk attitudes and three technologies characterised by different market maturity	Ma et al. (2009)
	-	50 years	-	Socio-technical transitions in general	Bergmann et al. (2008)
	-	2050	Europe drawing on UK data	Transition of the European transport sector to sustainability	Köhler et al. (2009)
	-	500 time steps	-	Transitions to a sustainable economy including the analysis of technology lock-in situations and the transition to a low carbon energy system based on heterogeneous boundedly rational agents	Safarzynska (2009) Safarzynska & van den Bergh (2010)
Agent-based simulation in energy models	EMCAS	2021	South Korea	Generation expansion processes in liberalised electricity markets	Botterud et al. (2007)
	-	2030	Municipal energy system	Investment decisions in urban energy systems focussing on decentralised technologies	Wittmann (2008)
	-	2025	Switzerland	Spatial diffusion of agricultural biogas technology considering a GIS	Madlener & Schmid (2009)
	PowerACE	(1) Present (2) 2020	Germany	(1) Impact of renewable electricity generation on the electricity market. (2) Expansion of onshore wind energy in Germany	Sensfuss (2008) Sensfuss et al. (2008)
		Present	Germany	Learning algorithms in price building mechanisms on the electricity market and the impact of market structure and design on electricity prices	Weidlich & Veit (2008)
		(1) Present (2) 2030	Germany	(3) Investment decisions in the conventional power sector (4) Analysis of market power	Möst & Genoese (2009) Genoese et al. (2007a)
Agent-based simulation in other sectors	-	20 years	Chile	Adoption decisions of agricultural innovations by farms	Berger (2001) Berger (2004) Berger & Schreinemachers (2006)
	-	2020	Model region in Southern Germany	Diffusion of water-saving innovations	Schwarz (2007) Schwarz & Ernst (2007)

Source: Own illustration

4 Resource availability and techno-economic characterisation of renewable energies

The potential future use of RES for energy conversion purposes is determined strongly by the resource availability and the corresponding energy conversion costs. Both factors differ from one RES to another to a certain extent. Additional, energy conversion costs tend to vary within one RES according to various factors including the meteorological regime or the plant size. These circumstances suggest an in-depth assessment of cost-resource curves instead of a mere renewable potential analysis. Cost-resource curves applied in the simulation model should ideally meet some specific requirements including a high geographical resolution at least at country level and they should consider potentials, whose exploitation appears to be feasible in the long term. As cost-resource curves fulfilling these requirements are not available for all RET, an own assessment of cost-resource curves is realised and described in this chapter. It is the aim of this chapter to provide an assessment of cost-resource curves for RES including own estimations for selected technologies on the one hand and assessments based on literature available for the remaining technologies on the other hand. Derived cost-resource curves represent a crucial input for the developed simulation model PowerACE-ResInvest (see chapter 5).

This chapter starts with the explanation of the required terminology. Then, cost-resource curves are assessed for onshore wind and solar PV taking into account spatially explicit aspects. Subsequently, cost-resource curves are derived for biomass and the remaining renewable conversion technologies based on potential estimations available in literature. Due to the complex framework conditions in case of biomass including the variety of feedstock and conversion technologies available, as well as potential uses of biomass inside (heating, transport) or outside the energy sector, a more detailed description of the cost-resource curve assessment is provided. The characterisation of each RES and the respective conversion technologies is supplemented by an overview of learning rates available in literature in order to provide a basis for the dynamic sampling of the cost-resource curves. The section concludes with a summary and a conclusion on the obtained results.

4.1 Terminology

4.1.1 Definition of renewable potential categories

The total amount of resources available needs to be determined in a first step to derive detailed cost-resource curves for one RET. This amount corresponds to the energy resource potential, which can be differentiated into various categories according to the kind of restrictions being applied. According to definitions described by Resch et al (2008), Resch et al. (2009, p. 135-136) and the 'Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen' [WBGU] (2009, p. 102), the following potential categories are distinguished:

The **theoretical potential** comprises the entire physical energy supply available without considering any restrictions. It represents the theoretical maximum for the use of RES. In order to determine the **technical potential** the theoretical potential is reduced by considering technical and geographical constraints. Important technical and geographical restrictions that have to be considered are the available conversion technologies, conversion losses, location availability (e.g. possible locations to install wind turbines) or other limitations. The technical potential is dynamic as technology develops over time. By taking into consideration dynamic realisation restrictions such as maximum market growth rates, planning constraints as well as political and societal drivers, the **realisable potentia**l is derived. It represents the maximum potential that can be explored up to a certain point in time.

The estimation of factors limiting the renewable energy potential including for example the area available for the use of RES involves a certain degree of uncertainty. When estimating the area suited for a certain type of RET, competing land-use option have to be considered and balanced. On this account, existing potential estimations show broad ranges to some extent. These potential ranges estimated in other studies are compared for the selected technologies before dynamic cost-resource curves are derived.

4.1.2 Principle of dynamic cost-resource curves for RES

Cost-resource curves describe the amount of final energy that can be provided by means of a particular technology option at a certain cost level. Thus, techno-economic characteristics of the conversion technologies play a crucial role for the energetic use of RES besides resource availability. As existing technology options may develop over time in terms of improved efficiencies or reduced investments, dynamic aspects are integrated into the cost-resource curves, as described by Resch et al. (2004). In principle these cost levels correspond approximately to a continuous sequence, which tends to be converted in discrete levels in order to reduce calculation time. Figure 4-1 provides a schematic representation of the basic principle of the dynamic cost-resource curves.

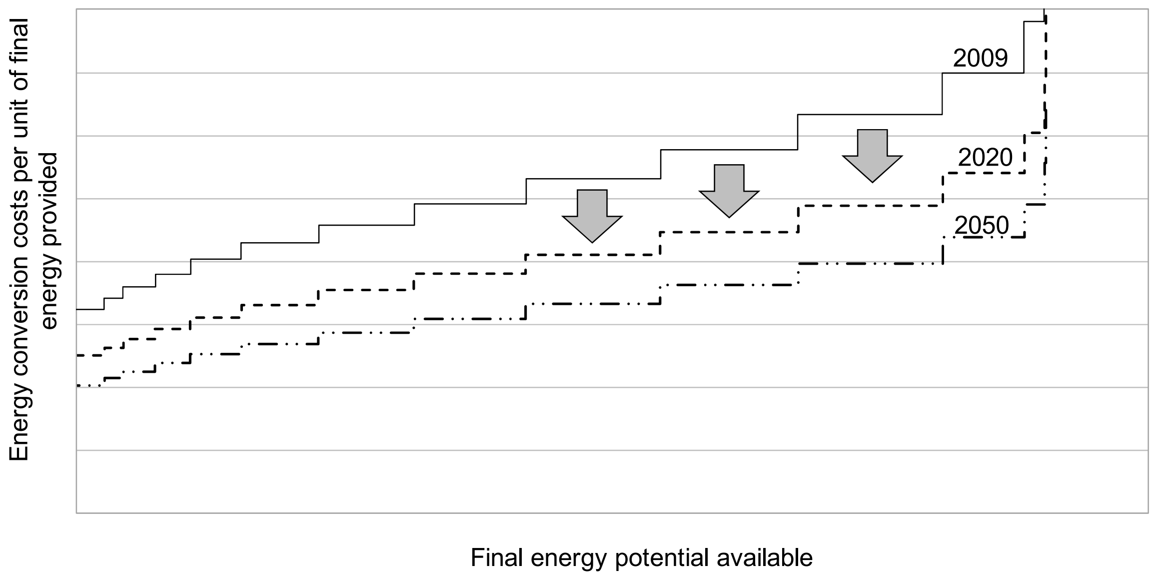

Figure 4-1 Schematic representation of the basic principle of dynamic cost-resource curves
Source: Own illustration

The factors that determine the economic performance of the conversion technologies vary between the different RES. In case of wind energy, electricity generation costs depend strongly on the local wind regime and the turbine characteristics including hub height and the rotor diameter, whilst feedstock price, the type and the size of the conversion plant represent important determinants for electricity generation costs of biomass-based power plants.

The resulting cost-resource curves derived in this chapter are presented exemplarily in terms of static cost-resource curves assuming current techno-economic parameters (2009). Subsequently, the potential stages are integrated into the simulation model in terms of a combination of available capacity potential and the corresponding economic and technical parameters. This means that a preliminary stage of the cost-resource curves is fed into the simulation model. Based on the dynamically evolving techno-economic parameters, the simulation model calculates the economic performance of a certain potential stage endogenously on a yearly basis (see section 5.5.5). The concept of experience curves reflecting aspects of technological change is applied to integrate the dynamic evolution of electricity generation costs in the future. According to this approach the pathway of cost reductions is characterised by the learning rate which describes the percental cost reduction involved by each doubling of the production capacity (Neij 2008). Besides the underlying causes for cost reductions in terms of cumulative experience or 'learning-by-doing' additional factors based on cumulated knowledge or 'learning-by-searching' may affect the development of costs and have led to a new approach which is referred to as the 'two-factor learning curve' (Jamasb 2007). The consideration of learning aspects in this thesis is limited to the effects of cumulative experience.

4.2 Regional cost-resources curves for onshore wind energy

Wind turbines provide electrical energy by converting the wind’s kinetic power partly into a rotation, which in turn drives a current generator. As the provided electrical power depends on the cube of the wind speed, local wind regimes represent a crucial influencing factor on the feasible power output of a wind turbine (cf. Kaltschmitt et al. 2003, pp 276). Due to the strong dependence on the wind regime, wind power electricity is characterised by high fluctuations of the electricity output. This matter of fact poses a crucial challenge for system operation of electricity systems with a high share of wind power (cf. Holttinen et al. 2009, p. 12-27). Wind energy can be produced either by turbines installed onshore or alternatively by turbines constructed at sea, generally nearby the shoreline. Regional cost-resource curves are derived for onshore wind energy, whilst cost-resource curves for offshore wind energy are estimated based on data available in literature (see section 4.5.2).

4.2.1 Europe's wind power potential onshore – existing studies

In this section studies that calculated the onshore wind potential for Europe are compared. With regard to the comparison it should be taken into account that the regional coverage of the studies available differs slightly. Most of the existing studies calculated the technical onshore wind energy potential on a global level and depicted figures for a zone of Western Europe including the EU15 and Norway, Switzerland and Turkey, whereas a study which estimated the realisable potential up to 2020 (Ragwitz et al. 2005b) focuses on the EU and derived detailed potentials on country level for the EU-MS as of 2006. The estimated potentials are shown according to their availability in Figure 4-2 referring to the EU15 countries and Norway and to Switzerland and Turkey in some cases.

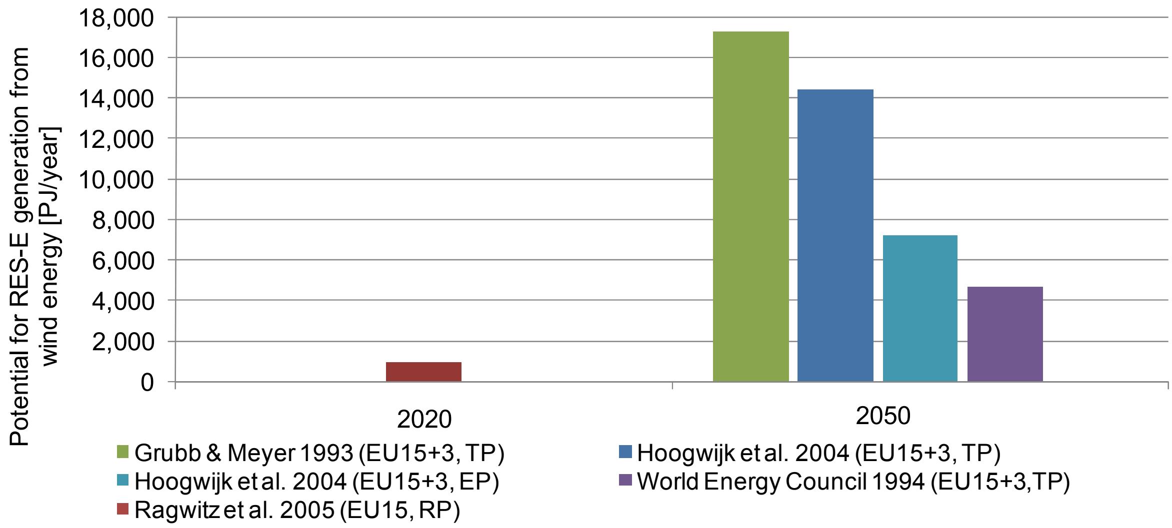

Figure 4-2 Comparison of the onshore wind primary energy potential in Europe. EU15+3 includes Norway, Switzerland and Turkey, TP means 'Technical Potential', EP represents the 'Economic Potential' and includes costs below 0.10 $/kWh and RP stands for 'Realisable Potential'

The highest onshore wind potential shown in Figure 4-2 for Western Europe was estimated to be 17,280 PJ/year using land-use constraints for wind electricity generation (exclusion of cities, forests, inaccessible mountains) as well as social and environmental constraints in order to determine the technical potential based on the theoretical potential (Grubb & Meyer 1993). Only sites with an average wind speed above 6 m/s were included assuming a conversion efficiency factor of 33 %.

Results from the global potential study carried out by Hoogwijk et al. (2004) indicate a technical onshore wind potential of about 14,400 PJ/year for Western Europe considering wind speeds exceeding 4 m/s at 10 m. Hoogwijk et al. (2004) took into consideration economic aspects and reported a halved potential assuming the inclusion of sites with electricity generation costs below 0.1 $/kWh.

Based on the assumption that 4 % of the area with a wind speed exceeding 5.1 m/s at 10 m are available for the use of wind energy, the World Energy Council (1994) assessed the technical onshore wind energy potential to be 4,680 PJ/year. A further restriction within this study was that areas with a distance of more than 50 km from the existing grid were excluded.

Compared to the technical potentials the realisable midterm-potential until 2020 estimated by Ragwitz et al. (2005) shows significantly lower values. Only 964 PJ/year are expected to be realisable realistically until 2020. This can mainly be explained by the assumption of additional barriers such as grid restrictions, planning constraints or limited annual growth rates limit the available onshore wind energy potential up to 2020.

As electricity generation costs of electricity from wind power plants largely depend on local wind regimes, not only the overall potential but also the corresponding costs of electricity generation have to be considered. The analysed studies aiming at the estimation of the European wind power potential so far, either represented a global assessment reporting on Europe as a whole (e.g. Grupp & Meyer 1993; World Energy Council 1994; Hoogwijk et al. 2004, Archer et al. 2005) or represent an EU-focussed study not taking into account detailed local wind velocities and land availabilities (Ragwitz et al. 2005). Therefore, it was decided to realise an own study wherein detailed cost-resource curves for onshore wind energy in the EU are derived on a regional level considering a time horizon up to 2050. In addition, this analysis takes into account dynamic aspects regarding future costs and technological developments. The resulting cost-resource curves estimated within this analysis serve as a key input for the simulation model PowerACE-ResInvest.

4.2.2 Methodological approach

In this analysis, the realisable potential for onshore wind energy up to the year 2050 is estimated based on the assumption that dynamic realisation restrictions might be overcome in the long term. This fact implies that the realisable potential up to 2050 corresponds approximately to the technical potential. Social constraints are considered to some extent. In this way, minimum distances to urban area are taken into account and the capacity density is assumed to be lower than the amount that would be technically feasible. Aspects regarding the integration of wind energy into the electricity system are not considered within this study. The derivation of the onshore wind cost-resource curves is based on the estimation of the wind energy potential on the one hand and on the calculation of the related costs determined in particular by the investment and the local wind regimes on the other hand. In particular two main factors influence the available wind energy potential, the local wind regime influencing the energy yield of a turbine and the land area available for construction of wind turbines which determines the total available wind capacity potential. A schematic overview of the applied methodology is depicted in Figure 4-3.

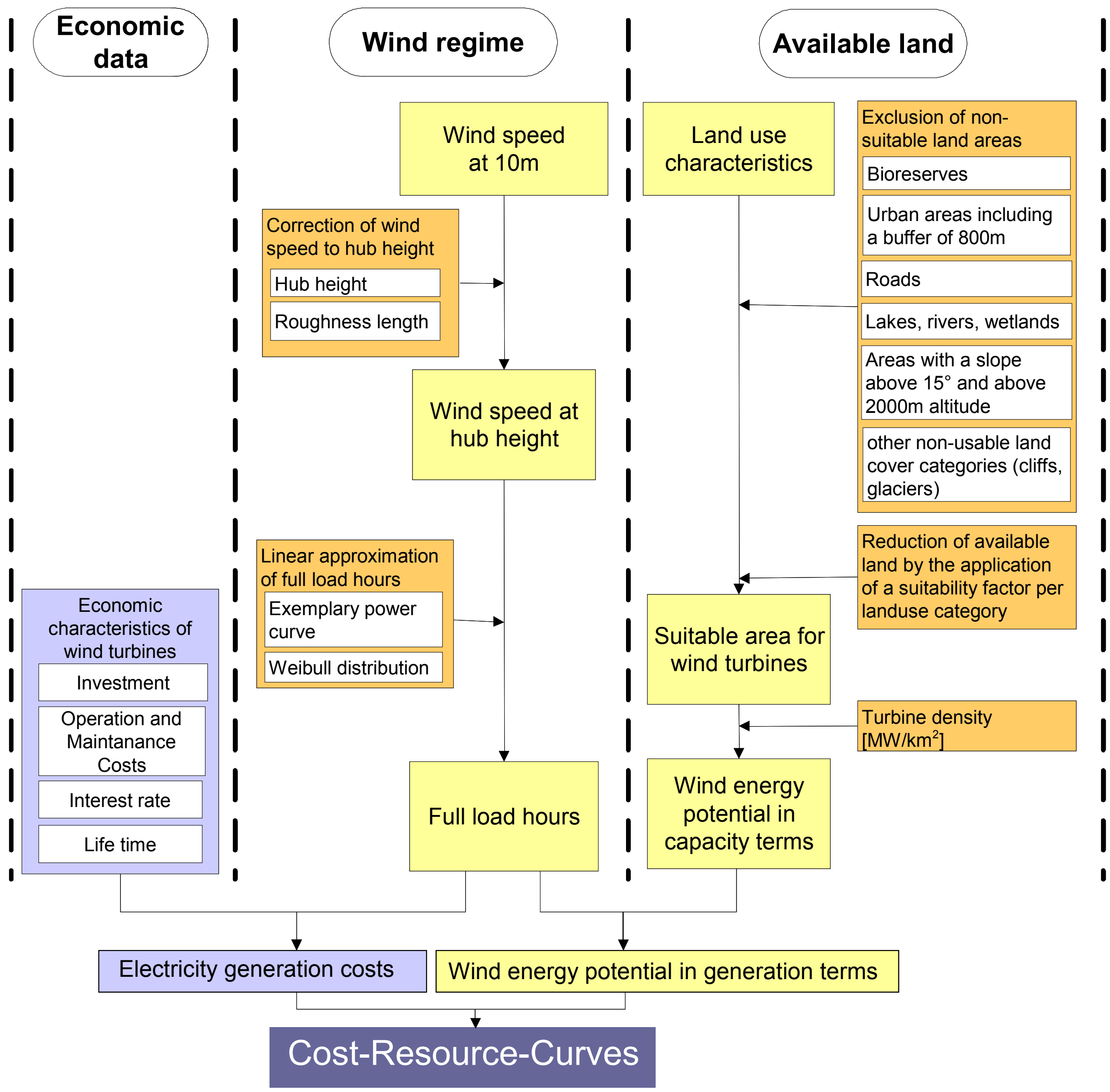

Figure 4-3 Scheme of applied approach for the determination of the cost-resource curves for onshore wind electricity

Source: Own illustration

To process the spatial data required for this analysis, the commercial geographical information system (GIS) ArcView provided by ESRI is applied[25]. Generally speaking, GIS are computer systems applied to acquire, store, manage, process, manipulate and display geographic data (Bill 1999, p. 4). In principle, a GIS can handle geographic data either in terms of vector data or raster datasets. Whilst vector data are characterised by discrete sets of information on the features and the respective spatial data, raster datasets consist of grid cells characterised by a certain feature. In this analysis, raster datasets are used to derive the regional cost-resource curves.

25 More information can be found at: http://www.esri.com/.

In a first step regional wind velocities are transformed into full-load hours, one of the relevant factors determining the economic profitability of wind electricity production[26]. In a second step the available area for the construction of wind-turbines is estimated. Finally, both results are combined in order to determine the feasible electricity output in each region. Subsequently, the determination of the full load hours, the estimation of the available land and the cost calculations are described.

For the calculation of the full-load hours, a wind speed dataset created by the Climate Research Unit belonging to the University of East Anglia was used (cf. New et al. 2002). This wind speed data was derived by means of geo-statistical interpolation using monthly weather measurements reported from 3,950 stations worldwide in the period between 1961 and 1990. The data was interpolated to a geographical resolution of 10' x 10'[27]. Although measurement size varied between the different locations between 2 m and 20°m, the authors recommend assuming a measurement height of 10 m representing the large majority of known heights. Due to the time-consuming calculation process of the geographical information system, monthly wind speed data is aggregated to annual averages.

As wind speed varies depending on the altitude, the wind speeds were corrected to turbine height according to the barometric formula (see formula (4.1))[28].

$$v_h = v_{ref} * \frac{ln\left(\frac{h}{z_0}\right)}{ln\left(\frac{z_{ref}}{z_0}\right)} \qquad (4.1)$$

where:

h	*Hub height*
v_{ref}	*Wind speed at reference height*
v_h	*Wind speed at hub height*
z_0	*Roughness length*
z_{ref}	*Reference height*

The hub height is assumed to be at 80 m within this study. For the wind speed correction to hub height, the roughness length is assumed to amount to 0.0024 m which corresponds to a roughness class of 0.5 according to the definition of Troen et al. (1989). Thereby, one should keep in mind, that this simplified assumption may lead to an underestimation of the wind speeds at hub height in particular in complex and uneven terrains. In addition, the application of the neutral logarithmic wind profile only applies for neu-

26 The full-load hours represent the ratio between the annual electricity output of a wind turbine and its rated capacity.

27 The geographical resolution is expressed in angular measurement (arcminutes). The grid cell size in square meters depends on the latitude. One arcminute equals to one sixtieth degree or to about 1.86 km at the equator.

28 Obstacles on the ground might slow down wind velocities significantly. The surface texture influences the correction of the wind speeds to hub height. The indicator for the surface texture is generally expressed by the roughness length which describes the altitude above ground level, where the wind velocity theoretically amounts to zero.

tral weather conditions, implying that the effects of thermal stratification are ignored leading to an error of the wind speed correction to hub height. Focken et al. (2003) observed that the application of the barometric formula tends to underestimate wind speed corrections using exclusively the Barometric formula for stable weather situations at a Dutch measurement station.

The expected energy yield of a wind turbine is determined by the turbine characteristics and the local wind regime. Thereby, the statistical distribution of wind speeds has to be taken into account. Usually, the variations in wind speed are described by means of a Weibull distribution (Hau 2003). The Weibull density function reads as follows:

$$p(v) = \frac{k}{a}\left(\frac{v}{a}\right)^{k-1} \cdot e^{-\left(\frac{v}{a}\right)^{k}} \tag{4.2}$$

where:

k	*Shape factor*
a	*Scale parameter [m/s]*
v	*Wind speed [m/s]*

The shape factor k might take values between 1.5 and 3. Higher values of the k-factor represent little variations in wind speed whereas lower values indicate higher wind speed variability (Seguro & Lambert 2000). The scale parameter is related to the average wind speed and the k-factor, following a Gamma-function (see formula (4.3)).

$$a = \mu(v) * \frac{1}{\Gamma\left(1+\frac{1}{k}\right)} \tag{4.4}$$

Due to the absence of information about wind speed variability in all EU-countries on regional level, a k-factor of 2, representing moderately gusty winds, is assumed as proposed by Seguro (2000) for the approximation of full-load hours.

Assuming a k-factor of 2, the Weibull function is converted into a Rayleigh function, as shown in formula (4.5).

$$p(v) = 2 * \left(\frac{v}{c^2}\right) * e^{-\left(\frac{v}{c}\right)^2} \tag{4.6}$$

The relation between wind speed (v) and full-load hours (h) is approximated by using a linear regression based on power curves. It should be noted, that this correlation is assumed to be valid for the wind speed interval from 4 m/s to 9 m/s.

Figure 4-4 shows this relation for selected turbine types. As average turbine sizes of newly installed turbines in the five European countries with the largest annual capacity increase of onshore wind plants in 2007 (DE, ES, FR, IT, UK) have increased during the last years and are currently equalling almost 2 MW (EurObserv'ER 2008), a 2 MW turbine of Vestas (Vestas V80) was selected as a reference turbine for the linear regression.

Following the linear equation

$$h = m * v + b \tag{4.7}$$

m was estimated to be $728 \frac{s*h}{m*a}$ and b amounted to $-2{,}368 \frac{h}{a}$ assuming the characteristics of the selected reference turbine[29].

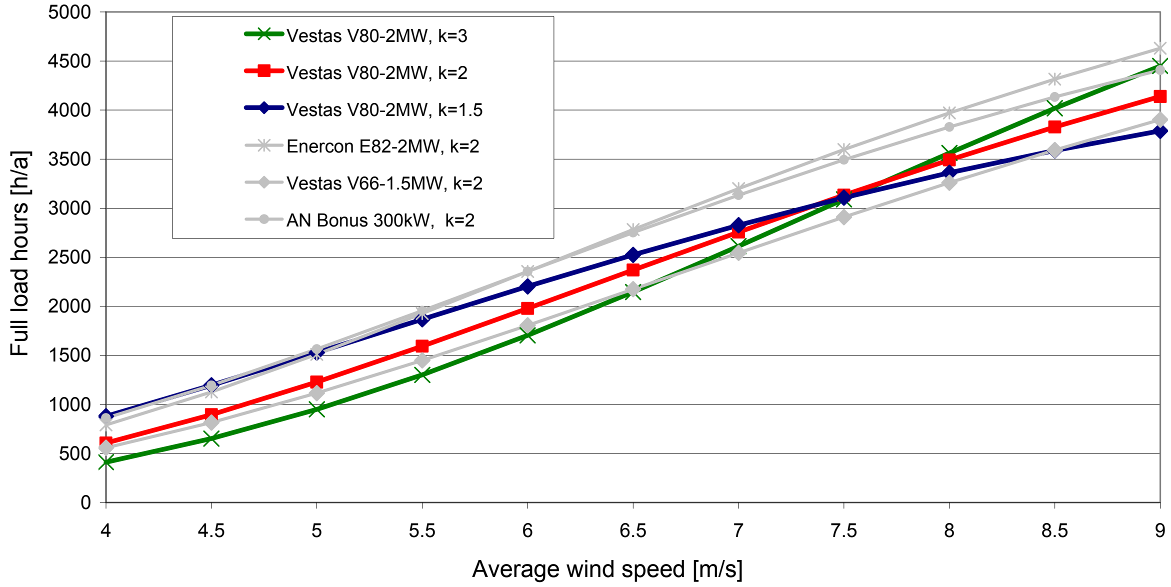

Figure 4-4 Approximation of the relation between full load hours and average wind speeds based on power curves of existing wind turbines

Source: Own illustration

The full-load hours are calculated for a range of average annual wind speeds between 4 m/s and 9 m/s on hub height. In order to avoid that locations with insufficient wind availability are included in the potential calculation, only areas where full-load hours exceed 1,300 h/a are considered. Assuming the described linear correlation of the reference power curve this lower limit corresponds to an average wind speed of slightly above 5 m/s at hub height. Aiming at a facilitation of the calculations, the continuous full-load hours are transformed into discrete intervals of 100 h/a.

The estimation of the available area for the construction of wind turbines is based on the CORINE land-cover database created by the European Environment Agency [EEA] (CORINE land cover 2000)[30]. Existing constraints are considered and used for a reduction of the suitable areas for the construction of wind turbines. The first step is the exclusion of naturally protected areas. Thereby, the protected area management categories I, II and III as declared by the WDPA Consortium (2006) are cut out from the available land area.

29 The corresponding Pearson product-moment correlation coefficient amounts to 0.986.

30 Copyright EEA, Copenhagen, 2007. Data available at http://www.eea.europa.eu. For further information about the data the reader is referred to Nunes de Lima (2005).

Secondly, urban areas and all artificial surfaces as for instance roads are removed from the suitable area as well as natural areas not suitable for the construction of wind turbines including rivers or lakes and other non-usable land cover categories such as cliffs or glaciers. In order to account for the social acceptability of wind turbines, a buffer with a radius of 800 m distance to habitat areas further diminishes the available land area.

Mountainous terrain which is difficult to access including areas above 2000 m of altitude and slopes above 15° are assumed not to be suitable for the construction of wind turbines. The exclusion of these terrains difficult to access is based on an intersection of the CORINE-data with a geographical dataset containing information about the altitude (SRTM 2004).

In a next step various suitability factors for the remaining available area according to their CORINE-category are assumed in order to account for the fact, that only partial use can be made of the available land, which is already used for other purposes. In this way suitability factors for sylvan regions are assigned a comparatively low suitability of 10 %, whereas half of the exiting grassland is assumed to be available for the use of wind energy plants. Table A-2 in the Annex shows the suitability factors that have been assumed to be available for the construction of wind energy plants for each CORINE land use category.

Compared to other studies, that assumed higher turbine densities of 4 MW/km^2 (Hoogwijk et al. 2004) or 9 MW/km^2 (Archer et al. 2005), a feasible capacity density of 3 MW/km^2 is assumed in order to account for social acceptability. This density factor is used to calculate the totally available area suitable for wind energy[31].

Subsequently, the investigated area is combined with the corresponding full-load hours in order to illustrate the combination of available wind power capacity and full-load hours. Losses induced by the aerodynamic interferences of wind turbines in wind parks are not considered within this study. For more information about this effect the reader is referred to (Hau 2003).

The last step of the derivation of the cost-resource curves requires the calculation of the corresponding electricity generation costs. As wind power generation is strongly capital-intensive, electricity generation costs depend in particular on the amount of the produced electricity output, determined by the full-load hours. Therefore, we determine the electricity generation costs for each potential step based on economic parameters shown in Table 4-1.

Table 4-1 Assumptions for the calculation of the electricity generation costs

	Investment	**O&M costs**	**Plant size**	**Lifetime**
Technology	*[€/kW_{el}]*	*[€/(kW_{el}*a)]*	*MW*	*[a]*
Wind onshore	1,380	41	2	20

Source: (Prideaux & Harrison 2009)

31 Only for Austria, Bulgaria, Hungary, Malta and Slovenia a capacity density of 5 MW/km^2 is assumed.

Finally, the respective electricity generation costs are assigned to the derived combination of wind power capacity and full-load hours and the complete cost-resource curves are derived.

4.2.3 Resulting onshore wind resources and cost-resource curves

Results (see Table 4-2) show that there is a considerable long-term potential for the use of onshore wind energy in the EU amounting to roughly 2 PWh per year neglecting existing grid constraints and considering areas with a wind regime implying more than 1,300 full-load hours per year. Contrasting the estimated wind energy potential to the EU's electricity demand of 3.8 PWh by 2030 predicted within the IEA Reference Scenario(International Energy Agency [IEA] 2007), it becomes clear, that wind energy might contribute significantly to European electricity supply on a long-term horizon. Though, one should keep in mind, that high penetration rates of wind energy in the electricity system might involve several problems provoked by the intermittent nature of wind energy and the existing divergence between wind electricity supply and demand for electricity on a high-resolution time scale.

Table 4-2 Estimated realisable onshore wind potential up to 2050

Country	**Generation potential [GWh]**	**Capacity potential [MW]**	**Average full load hours [h/a]**
Austria	9,780	6,061	1,613
Belgium	7,815	4,185	1,867
Bulgaria	6,938	4,420	1,570
Cyprus	1,470	1,096	1,342
Czech Republic	54,327	25,961	2,093
Germany	105,906	54,451	1,945
Denmark	81,093	25,476	3,183
Estonia	35,885	19,800	1,812
Spain	189,348	117,884	1,606
Finland	24,310	15,553	1,563
France	281,421	158,332	1,777
Greece	16,288	8,657	1,882
Hungary	2,981	2,078	1,434
Ireland	127,187	50,205	2,533
Italy	26,947	14,725	1,830
Latvia	26,297	15,323	1,716
Lithuania	8,310	4,896	1,697
Luxembourg	1,111	566	1,964
Malta	139	71	1,971
The Netherlands	37,138	16,850	2,204
Poland	103,692	65,310	1,588
Portugal	58,060	36,459	1,592
Romania	13,131	7,640	1,719
Sweden	294,264	152,905	1,924
Slovenia	520	313	1,660
Slovakia	5,914	3,895	1,518
United Kingdom	442,661	178,920	2,474
EU	**1,962,932**	**992,032**	**1,979**

Source: Own calculations

Observing the spatial distribution of the regional wind regimes in terms of full-load hours in Figure 4-5, one can see that in particular the United Kingdom, Ireland and Denmark dispose of favourable wind conditions. By contrast, Eastern Mediterranean countries seem to be less favourable for the use of onshore wind energy.

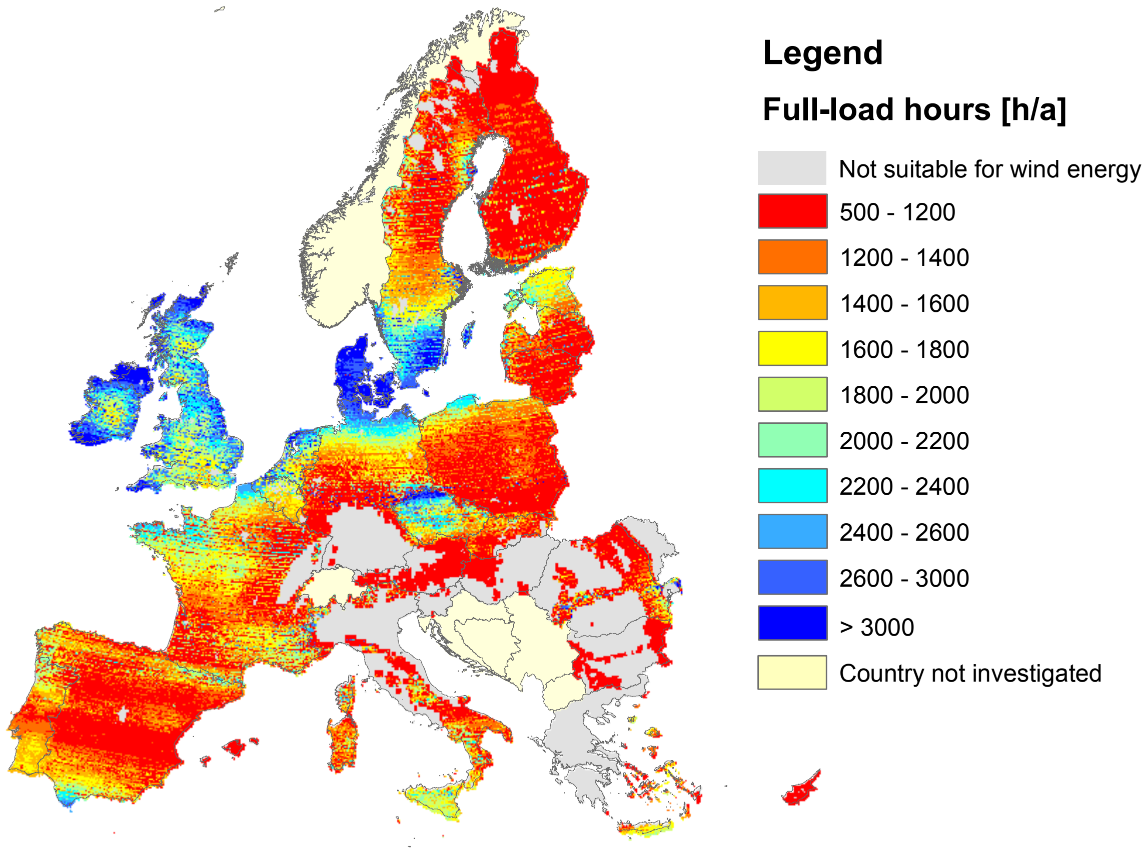

Figure 4-5 Annual full-load hours for onshore wind energy in the EU
Source: Own calculations

The corresponding costs of each potential step represented in Figure 4-6 for Western European countries (EU15) show that at present (2009) wind electricity generation costs range between 4 € Cents/kWh and 12 € Cents/kWh corresponding to the lower full-load hour limit of 1300 h/a. Besides favourable wind conditions the United Kingdom disposes of a considerable surface area potential. According to the results of this analysis, the total realisable onshore wind potential in the United Kingdom amounts to 446 TWh. Comparing this magnitude to the national electricity demand of 397 TWh in 2007 (Eurostat 2010), the onshore wind energy potential available up to 2050 exceeds current national electricity demand in the United Kingdom. As already stated before, this does not necessarily mean, that total electricity generation could be covered exclusively by wind energy plants due the variable character of the wind electricity output. Further countries with favourable wind resource conditions and a lower area availability are Denmark and Ireland. Looking at the Spanish cost-resource curve, a considerable wind power potential appears to be available, but associated electricity generation costs are on a higher level than in North Sea countries. While the total wind energy generation potential of France and Sweden amounts to a similar magnitude, wind conditions in Sweden seem to be comparatively more favourable.

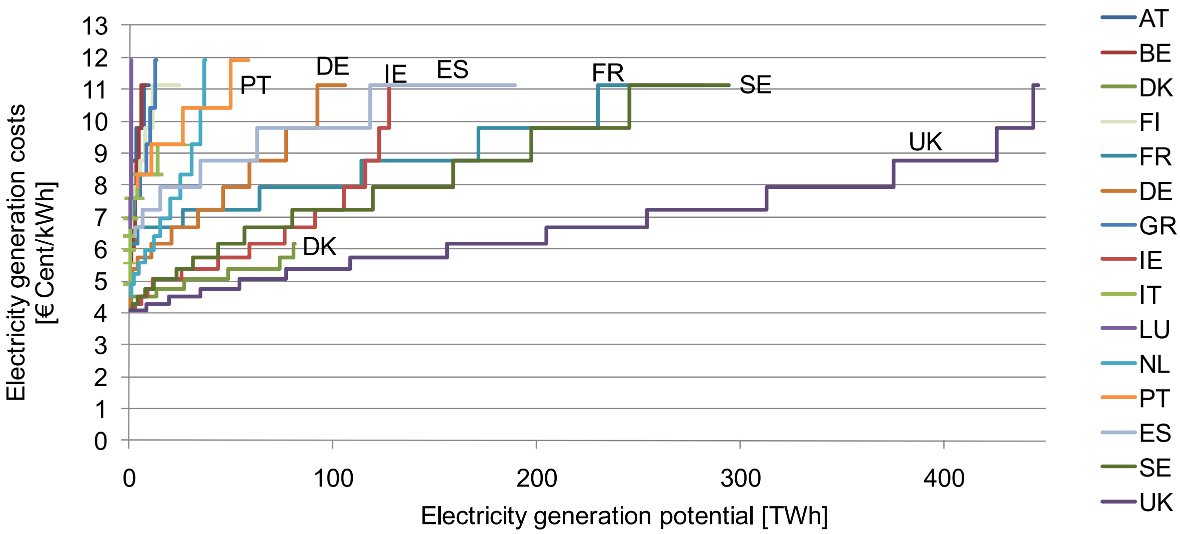

Figure 4-6 Derived cost-resource curves for onshore wind energy in the EU15 for 2009
Source: Own calculations

Observing the current cost-resource curves for Eastern European countries (EU12) in Figure 4-7, it becomes clear, that electricity generation costs of onshore wind energy tend to be generally higher than in the EU15. In addition, less land area is available for the construction of wind turbines. Whilst the Czech Republic disposes of the most favourable wind conditions in the EU12 leading to average full-load hours of 2,093 h/a, the largest potential in terms of total generation potential is available in Poland.

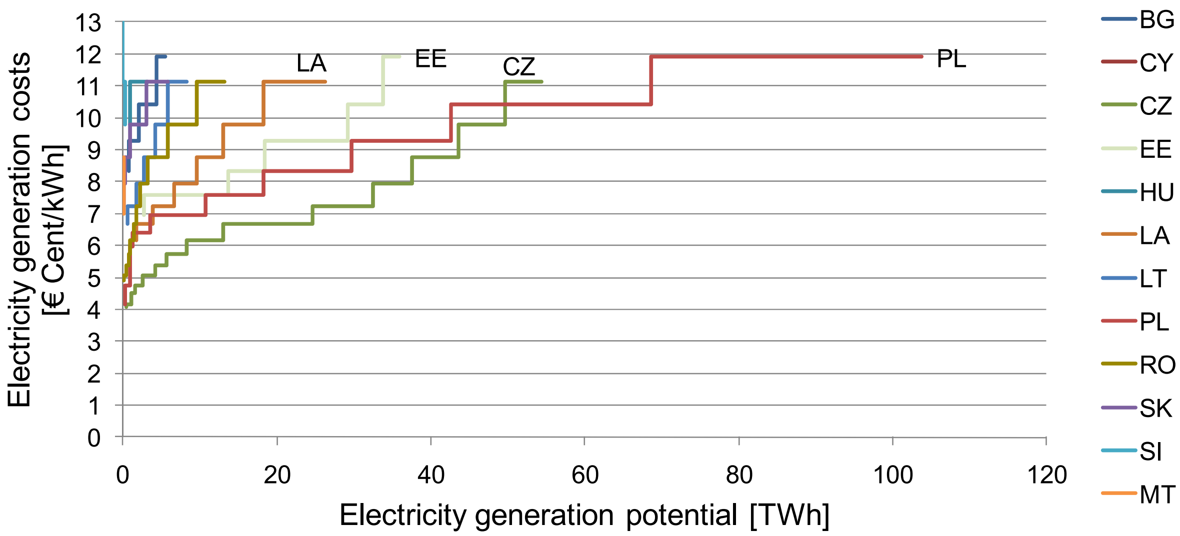

Figure 4-7 Derived cost-resource curves for onshore wind energy in the EU12 for 2009
Source: Own calculations

4.2.4 Learning rates

With an increased use of wind energy plants their techno-economic characteristics have been changing over time. Thus, various factors such as increasing turbine sizes and hub heights have induced reductions in the specific investment per capacity installed. In addition, yields of turbines have been increasing as a result of technological improvements. Available studies in literature about experience curves for onshore wind power plants investigated the cost reduction of wind turbines per unit of capacity installed or, taking into account potential technological developments, the cost reduction per unit of electricity generated (see Table 4-3). Plotting the cost development of wind power plants against the cumulative capacity, learning rates ranging from 4 to 20 % have been estimated in literature. As expected, learning rates set against electricity production are higher amounting to between 12 and 32 %.

Table 4-3 Overview of exemplary learning rates for onshore wind energy

Technology	Geographical coverage	Time frame	Learning rate [%]	Cost indicator	Experience indicator	Author
Wind onshore power plants	Denmark	1981-2000	10	Investment	Cumulative capacity	Neij et al. (2003)
	Spain	1984-2000	9			Neij et al. (2003)
	Sweden	1994-2000	4			Neij et al. (2003)
		1995-2000	12			Neij et al. (2003)
	Spanish prices, global devel-opment	1990-2001	15 - 20	Investment	Cumulative capacity	Junginger et al. (2005)
	British prices, global devel-opment	1992-2001	19 - 21			
	Global	1980-1998	15.7	Investment	Cumulative capacity	Jamasb (2007
	Danish manufacturers	1981-2000	14	Specific pro-duction costs	Cumulative capacity	Neij et al. (2003, p. 26)
	German manufacturers	1991-2000	12			
	USA	1985-1994	32	Specific pro-duction costs	Cumulative electricity production	International Energy Agency [IEA] (2000, p. 54)
	EU	1980-1995	18	Specific pro-duction costs	Cumulative electricity production	International Energy Agency [IEA] (2000, p. 43)

4.2.5 Discussion of results

In this analysis the feasible contribution of onshore wind energy up to 2050 has been estimated. Detailed cost-resource curves for onshore wind energy have been derived on a regional level for all EU-MS considering present costs as well as possible future cost reductions. Due to the strong spatial dependence of the potential and costs of wind power a geographical information system (GIS) was applied in order to take into account the geographical characteristics of both technologies. Some simplifying assumptions were made to meet the challenges resulting from the broad geographical scope and a high spatial resolution. In this way, the extrapolation of the wind speed from an altitude of 10 m to the assumed hub height of 80 m leads to an error in particular in continental areas, as the assumption of neutral atmospheric stability conditions does not fit perfectly with real weather conditions. The potential estimations are based on average annual wind speeds and thus wind speed variability is assumed to be the same in all EU-MS. A further simplification represents the selection of one reference turbine. As different turbine types tend to be used for lower wind speeds, the possible power output in lower wind speed zones might be underestimated. Furthermore, one should consider the limitations in spatial accuracy of the used wind speeds given that the dataset is taken from a global wind speed data derived based on geo-statistical interpolation. Given the wide geographical scope and the time horizon the above mentioned limitations appear to be acceptable considering the overall intention to estimate the magnitude of available renewables potential for the EU as a whole and the corresponding electricity generation costs.

4.3 Cost-resource curves for solar PV electricity

The direct conversion of solar irradiation into electrical energy occurs by means of the photovoltaic effect, in which photons induce the emergence of an electrical potential as a result of a separation of charge carriers in semi-conducting materials. In general a photovoltaic (PV) installation is composed of various modules of solar cells and the balance-of-system (BOS) including typically an inverter (given that the device is connected to the grid), cables and the mounting installation.

Solar cells may be produced using either silicon-based materials (crystalline or amorphous) on the one hand or non-silicon-based materials, such as Cadmium Telluride (CdTe), Copper-Indium-(Gallium)-Selene/Sulphate (CI(G)S) or organic materials on the other hand. Solar cells can e.g. be produced by sawing silicon wafers or alternatively by evaporating thin films of CdTe or silicon (predominantly amorphous). At present, the use of crystalline silicon-based materials dominates the photovoltaic technology. Thus, the market share of global crystalline silicon-based module production capacity is estimated to amount to 82 % in 2009, but the share of thin film based technologies is expected to increase in the future (European Photovoltaic Industry Association [EPIA] 2009, p. 16).

Besides the different types of solar cells, there are different options of mounting a PV installation. Solar PV power plants may either be constructed on the ground floor or integrated into buildings. In the latter case, the solar module can be mounted on top of the roof or integrated into the façade. Whilst most of the free-field installations tend to be larger installations of centralised character, building integrated PV installations can be characterised as decentralised installations. PV power plants may be constructed in remote areas without a connection to the electricity grid (off-grid installation) or alternatively in terms of grid connected installations. The potential estimation realised in this thesis is limited to grid-connected PV applications, as the simulation model PowerACE-ResInvest focuses on the grid-connected electricity system.

The electricity output of PV applications is variable depending on the solar irradiance. Compared to the variability of electricity output generated with wind turbines, the supply of solar PV electricity correlates better with the demand for electricity.

4.3.1 Europe's solar PV potential – existing studies

The overall theoretical potential for the use of solar PV energy in Europe is vast. According to Hoogwijk (2004, p. 157) the theoretical potential in terms of solar irradiance reaching the earth amounts to 14,400 EJ/year only in Western Europe including the respective OECD member states in Europe. Comparing the theoretical potential to the current gross final energy consumption of OECD European countries – 48 EJ in 2007 (Eurostat 2010) – it becomes clear, that the theoretical solar PV potential exceeds the current energy demand many times over. Looking at the technically available potential as shown in Figure 4-8, Hoogwijk (2004) places the technical potential of solar PV for OECD Europe at about 15 EJ/year, whilst according to Johansson et a. (1993) the lower limit of total solar potentials amounts to 25 EJ/year.

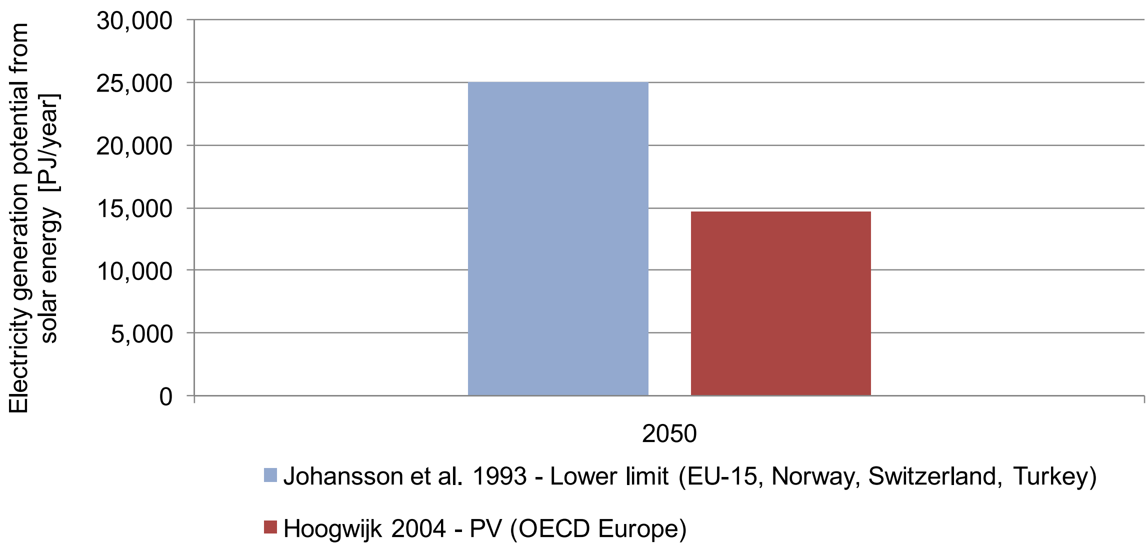

Figure 4-8 Potential estimations for electricity from solar energy

4.3.2 Methodological approach

The electricity generation potential for solar PV mainly depends on the area available for PV installations on the one hand and on the solar irradiation and the conversion efficiency of the modules on the other hand. Whereas the area available for PV installations determines particularly the amount of solar PV capacity that can be installed, solar irradiation affects the potential utilisation of a PV power plant installed. Similar to the weather-related influences of regionally varying wind conditions on the electricity output of wind power plants (see section 4.2), solar irradiation may differ considerably between and even within each country. Despite the vast potential available for solar PV electricity generation, the future use of PV technologies depends primarily on its economic performance. Electricity generation costs of PV in Europe still exceed clearly those of other RET, although considerable cost reductions have occurred during the last decade (IEA Photovoltaic Power Systems Program 2009, p. 28-29). Costs are still expected to experience further decreases in the future. The current economics of PV are characterised by high investments, stemming in particular from the upstream silicon production, and low conversion efficiencies ranging from 8 % - 25 % in production (cf. Kaltschmitt et al. 2003, p. 213). The predominant part of the investment is dominated by the module price.

Given the relevance of the investment for the overall economic performance of electricity from PV power plants, the respective electricity generation costs depend largely on the feasible power output determined by the solar irradiation. For this reason, an own potential estimation, taking into account regional solar irradiation data, is made. The detailed description of the methodology follows in the subsequent section.

The relevance of the regional solar irradiance for the economics of PV power plants suggests the use of a GIS, similar to the case of onshore wind energy (see section 4.2) for the derivation of cost-resource curves for solar PV. The cost-resource curves are to be derived for different types of plants including installations on free fields, roof-integrated and façade-integrated PV plants (see Figure 4-9).

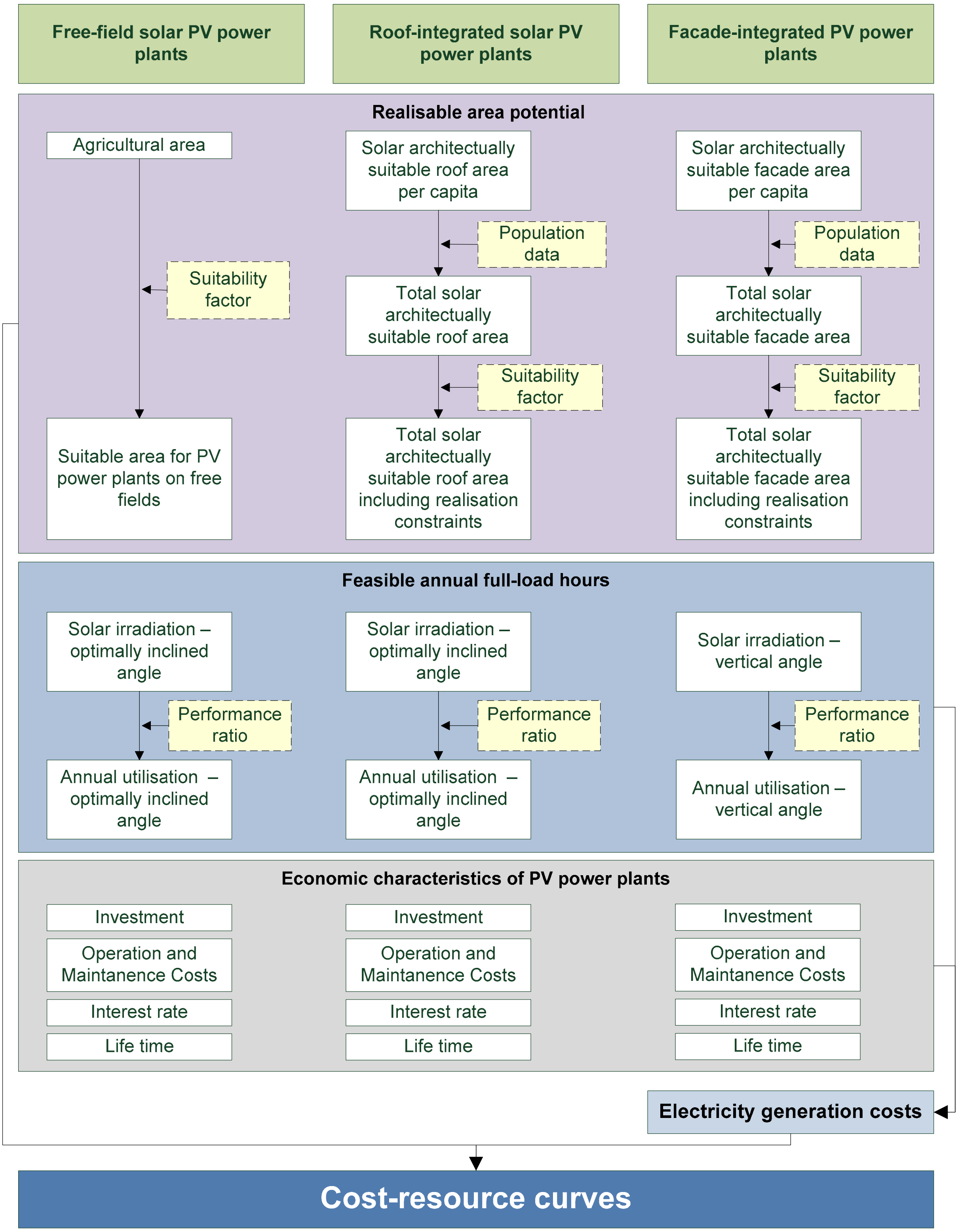

Figure 4-9 Scheme of applied approach for the determination of the cost-resource curves for electricity generation from solar PV power plants

Source: Own illustration

For all three PV power plant types the area available for the construction of a PV plant is calculated in a first step. Applying a factor, which describes the floor area required for the construction of all three PV plants investigated, the capacity potential is estimated in terms of peak power, corresponding to the rated output of a PV plant at standard test conditions (STC). STC assume an air temperature of 25 °C and a solar irradiation of 1000 W/m^2. By applying the peak power and the area requirement for 1 unit of peak power, no additional information on the module efficiency is required. Additional losses occurring in practice are considered in terms of an indicator reflecting the ratio between the actual power output of the system and the output under STC. This performance ratio includes deviations from STC such as a higher module temperature or lower solar irradiation, provoking a reduction of the actual power output of a PV plant. Likewise, efficiency losses occurring in other components of the PV plant than the module (cables, inverters) are considered within the performance ratio.

In a second step, the potential utilisation of the PV plants in terms of full-load hours is derived based on spatially explicit solar irradiation data for different angles depending on the type of the installation. In case of façade-integrated PV installations the vertical solar irradiation is taken, whereas free-field PV power plants are assumed to be mounted in an angle optimally inclined to maximise the power output. This angle is generally oriented southwards in the Northern hemisphere, but it may vary from region to region. The optimum angle is mainly determined by the geographical latitude, the proportion of diffuse to direct radiation and potential shadowing effects (Suri et al. 2007). The feasible orientation of roof-integrated modules can diverge depending on the roof type. The architecture predetermines the inclination of a solar PV power plant mounted on pitched roofs, whilst a flexible orientation is possible for mounting the PV installation on flat roofs. In case of pitched roofs additional losses occur due to deviations from the optimal azimuthal angle or deviations from the optimal angle of inclination. According to Quaschning (2000), losses of pitched roofs induced by deviations from the optimal angle range between 10 % and 15 % (Quaschning 2000, p. 46). Since no reliable information about the share of each roof type in the total roof area is available, the described losses are discarded in this analysis. Therefore, the cost-resource curves analysis is based on solar irradiation data for optimally inclined modules for roof-integrated PV power plants. Thus, the feasible utilisation for roof-integrated PV power plants is overestimated slightly.

Solar irradiation data is then processed within ArcGIS and the annual potential utilisation in terms of full-load hours is computed for each raster cell. In a next step, raster cells are aggregated into discrete full-load hour intervals in order to calculate the share of floor area belonging to a certain full-load hour interval on country level.

In contrast to the estimation of cost-resource curves for onshore wind energy no direct overlap of the available area with the corresponding full-load hours is performed. In fact, the available capacity potential is calculated based on the area availability and then divided up into the discrete full-load hour intervals on country level, that have been investigated by means of the solar irradiation data.

4.3.3 Suitable area for solar PV plants

As the construction of PV power plants on free fields has to compete with other purposes of the floor area, such as urban land use, agriculture or nature conservation, only a minor share of the floor area is supposed to be available for the construction of PV power plants. In this analysis the floor area suitable for PV installations is estimated based on the area used for agricultural purposes in each country. Only a certain share of the agricultural area is assumed to be suitable for PV power plants to account for competition with agricultural purposes. Additionally, dynamic realisation constraints such as visual impacts of large-scale PV power plants reduce the suitable area surface for the construction of PV power plants. Given the difficulty to quantify the impact of these factors on the estimation of the floor area suitable for the use of PV, the range of reasonable suitability factors is large and the determination of the respective suitability factor represents a challenging task. In order to account for the mentioned restrictions 0.5 % of the total agricultural area is assumed to be available for centralised PV in this analysis. Compared to another PV potential study realised by Soerensen et al. (1999, p. 92), who proposes to use 1 % of the range land for the construction of PV power plants and 5 % of the marginal land including scrubland and deserts, the estimated suitability factor is in a similar order of magnitude. The total available agricultural area of a country has been taken from Eurostat (2009) for the year 2000. Since the corresponding data for the year 2000 is not available for all countries, the data reported from previous years have been assumed.

Looking at building integrated PV power plants, the estimation of the floor area available depends on the roof and façade area suitable for PV installations. The calculation of the area available for building-integrated PV power plants is based on a study conducted by the International Energy Agency [IEA] (2002). The IEA put the roof area of all building types including agricultural, residential, industrial, commercial and other buildings suitable for PV power plants at 18 m^2 per capita and the respective façade area at 6.5 m^2 per capita. Multiplied with the population data, the overall area suitable for building integrated PV installations on roofs and on façades is computed. One main assumption made in this analysis is, that only half of the roof and façade area estimated by the IEA will be available for potential PV installations by the year 2050. In particular in case of roof-integrated solar PV plants this reduction accounts for the competition with solar heating panels.

Population data is based on a population scenario published by Eurostat (2008), the 'EUROPOP2008 convergence scenario'. In this scenario fertility, mortality and net migration between MS is assumed to converge in the long term. Eurostat estimates the population in the EU25 to increase from 495 million in 2008 to 515 million by 2050. For the calculation of the available roof and facade areas, the population scenario data of the year 2050 is assumed.

4.3.4 Solar radiation

For the estimation of the cost-resource curves, the solar radiation database PVGIS published by the Joint Research Centre 'Institute for Environment and Sustainability' (IES) in Ispra, Italy, is used as main input data. The 'Photovoltaic Geographic Information System' (PVGIS) is based on data processing of meteorological data from 566 measurement stations by means of the solar radiation model r.sun (cf. Suri & Hofierka 2004). Thereof, a raster dataset of global annual irradiation data (kWh/m^2) in Europe is publicly available for different inclination angles of the solar PV modules. The data is provided in terms of long-term annual averages for the period of 1981 – 1990 with a spatial resolution corresponding to a grid size of 5 arc-minutes[32].

Looking at the spatially explicit potential utilisation of optimally inclined PV modules in Figure 4-10, full-load hours in Scandinavian countries range from 650 h/a to roughly 800 h/a, whilst full-load hours of up to 1500 h/a can be achieved in Southern Europe in particular in Western Mediterranean regions including Portugal and Spain as well as in Sicily, Corsica and Crete.

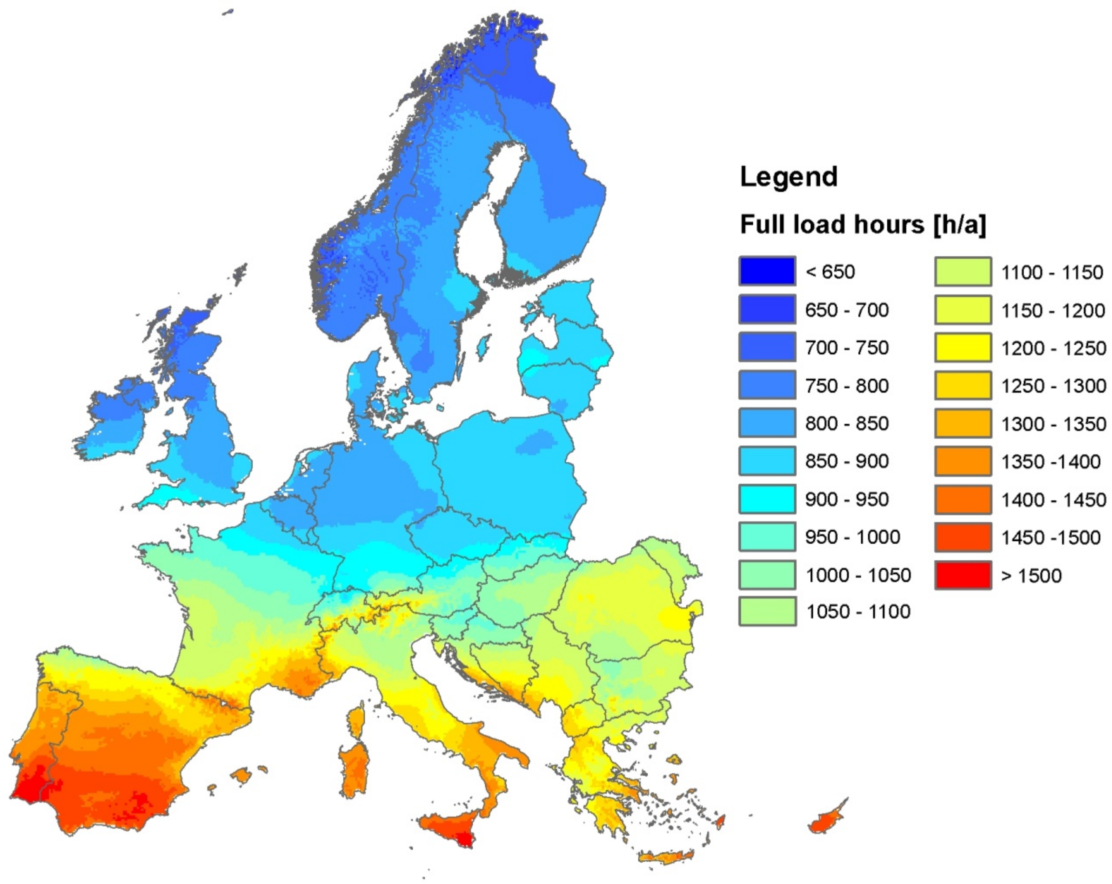

Figure 4-10 Annual full load hours of optimally inclined PV modules
Source: Own illustration based on data from Suri et al. (2007) and a PR of 0.75

32 A grid cell size of 5 arcminutes corresponds to a 9.3-km grid resolution at the equator.

In case of vertically inclined PV modules, the annual utilisation is considerably lower than in case of optimally inclined modules. According to the PVGIS data, annual full-load hours for facade-integrated PV modules range from about 450 h/a in Northern Europe to nearly 1000 h/a in Mediterranean countries. The regional annual full-load hours for vertically inclined facade-integrated PV modules differ considerably between Northern and Southern Europe (see Figure 4-11).

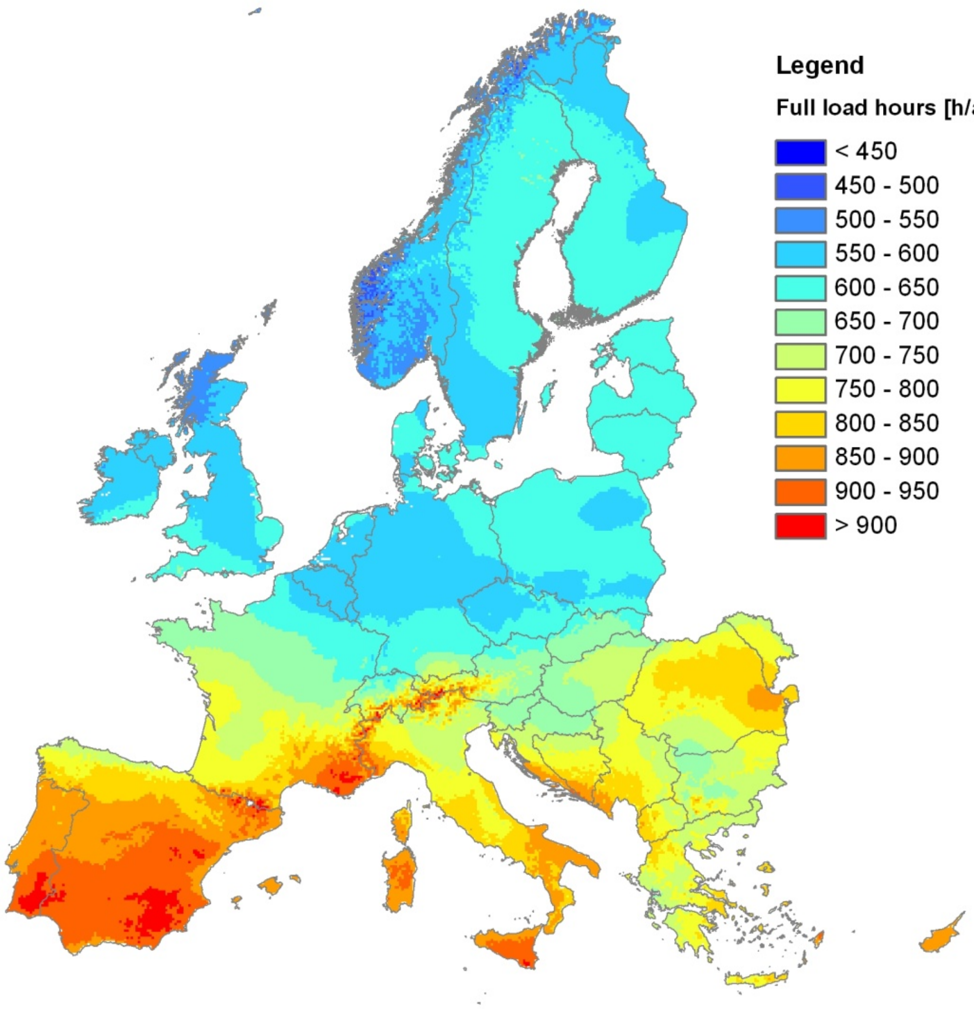

Figure 4-11 Annual full load hours of vertically inclined PV modules
Source: Own illustration based on data from Suri (2007) and a PR of 0.75

4.3.5 Resulting solar PV cost-resource curves

Finally, electricity generation costs are calculated for each of the previously investigated intervals which are characterised by the combination of the capacity potential and the corresponding electricity generation costs. Electricity generation costs are calculated based on the economic parameters shown in Table 4-4.

Table 4-4 Technical and economic characteristics of solar PV technologies considered for the determination of the cost-resource curves

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="4">Breakdown of investment into components</th><th colspan="4">Assumed techno-economic parameters for cost-resource curve assessment</th></tr>
<tr><th>Module</th><th>Inverter</th><th>Other costs (installation, cables, etc.)</th><th>Total invest-ment</th><th>Invest-ment</th><th>O&M costs</th><th>Life-time</th><th>Typical plant size</th></tr>
<tr><th colspan="2">Technology</th><th>[€/kW$_p$]</th><th>[€/kW$_p$]</th><th>[€/kW$_p$]</th><th>[€/kW$_p$]</th><th>[€/kW$_p$]</th><th>[€/ (kW$_p$*a)]</th><th>[a]</th><th>[MW$_p$]</th></tr>
<tr><td rowspan="3">Roof-integrated PV plant</td><td>Mono-crystalline silicon</td><td>1,910</td><td>500</td><td>450</td><td>2,860</td><td rowspan="3">3,000</td><td>60</td><td>20</td><td>0.05</td></tr>
<tr><td>Poly-crystalline silicon</td><td>2,090</td><td>500</td><td>450</td><td>3,040</td><td>60</td><td>20</td><td>0.05</td></tr>
<tr><td>Amorphous silicon</td><td>1,680</td><td>500</td><td>450</td><td>2,630</td><td>56</td><td>20</td><td>0.05</td></tr>
<tr><td colspan="2">Facade-integrated PV plant (mono- or poly-crystalline silicon)[33]</td><td>-</td><td>-</td><td>-</td><td>-</td><td>5,500</td><td>110</td><td>20</td><td>0.01</td></tr>
<tr><td colspan="2">PV plant on free fields (amorphous silicon)</td><td>1,680</td><td>400</td><td>400</td><td>2,480</td><td>2,600</td><td>52</td><td>20</td><td>1</td></tr>
</table>

Source: Own assumptions based on information from Bundesverband Solarwirtschaft e.V. [BSW-Solar] (2009); Kreutzmann (2009); Rutschmann & Siemer (2009)

According to the potential estimation, the resulting total potential for electricity generation with PV modules amounts to 1,760 TWh per year (see Figure 4-12). Comparing the available PV potential with the EU’s annual gross electricity demand in 2007 of 3,338 TWh, it becomes clear that PV electricity may contribute significantly to the EU’s electricity supply. Due to the floor area availability the dominating share of the total PV potential consists in non-building integrated PV power plants, corresponding to a total potential of 1,108 TWh per year or 63 % of the total solar PV potential. At the same time the cost-resource curve of free-field PV power plants features the lowest electricity generation costs of all three investigated plant types starting from 186 €/MWh to 411 €/MWh. According to the results, the corresponding electricity generation costs correspond to full-load hours between 700 h/a in Northern Europe and 1,500 h/a in Southern Europe. Looking at the roof-integrated solar PV plants, it turns out, that the overall potential amounts to 455 TWh per year. Due to higher initial investment requirements, electricity generation costs are higher compared to free-field plants ranging from 214 €/MWh to 474 €/MWh. The PV potential of facade-integrated plants is placed at 111 TWh per year and therewith accounts only for

33 Investment for facade-integrated PV power plants was reduced by 1,500 €/kW$_p$ in order to account for the substitution cost of the facade-material.

roughly 7 % of the total PV potential in the EU27. In addition, electricity generation costs for facade-integrated PV installations are by far the highest, amounting from 609 €/MWh to 1,218 €/MWh.

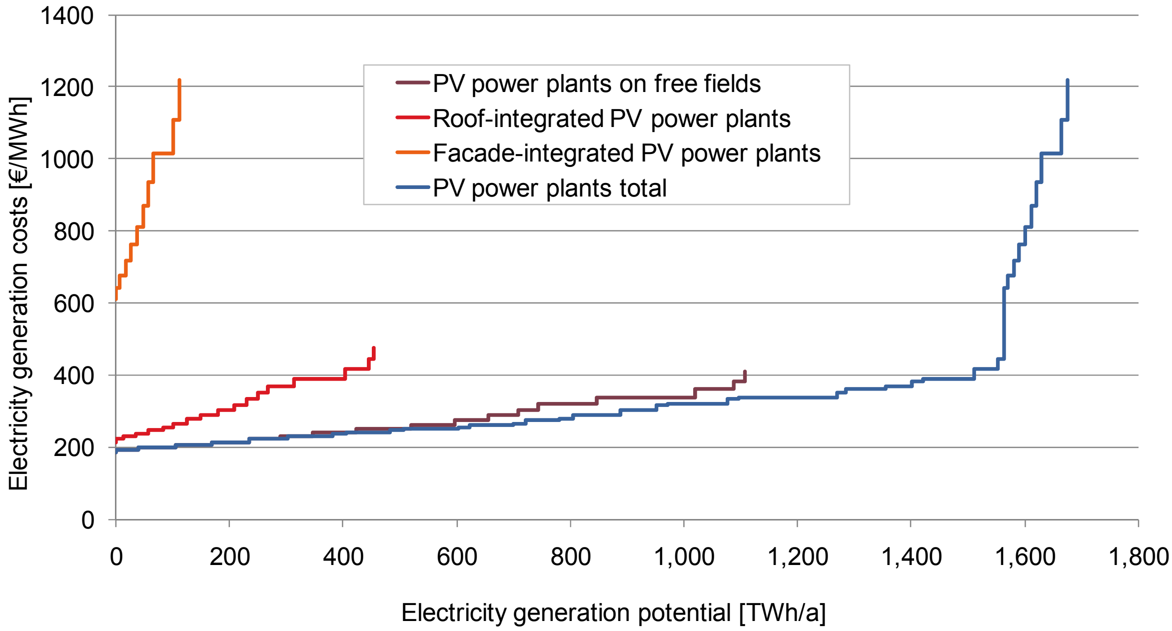

Figure 4-12 Derived cost-resource curves for solar PV technologies in the EU27 in 2009
Source: Own calculation

4.3.6 Learning rates

Due to the fact that electricity generation costs of solar PV power plants clearly exceed those of most others RET, particular importance is attached to potential future cost reductions. According to a survey of the German Solar Industry Association (BSW-Solar), the average system price of completely installed roof-integrated PV power plants decreased from 5,000 €/kWp the second quarter of 2006 to 3,263 €/kWp in the third quarter of 2009 (Bundesverband Solarwirtschaft e.V. [BSW-Solar] 2009). The learning rates observed in literature as shown in Table 4-5 were estimated based on time series up to 2005, which means that one should take into account that recent developments of the dynamic PV market are not reflected.

Table 4-5 Overview of exemplary learning rates for solar PV power plants

Technology	Geographical coverage	Time frame	Learning rate [%]	Cost indicator	Experience indicator	Author
PV power plant	Global	1979-2005	20	Investment (Module)	Cumulative capacity	Swanson (2006)
		1976-2001	20	Investment (Module)	Cumulative capacity	Schaeffer (2004)
		1987-2001	23			
		1989-2002	19.5	Investment (Module)	Cumulative capacity	Poponi (2003)
		1976-2002	25			
		1981-2000	23	Investment (Module)	Cumulative capacity	Parente et al. (2003)
	EU	1976-1996	16	Investment (Crystalline module)	Cumulative capacity	International Energy Agency [IEA] (2000)
		1987-1996	21			
		1985-1995	35	Electricity generation costs	Cumulative electricity generation	
	Global	Modelling assumption	20 - 23	Investment (Total plant)	Cumulative capacity	Uyterlinde et al. (2007)

4.3.7 Discussion of results

In this subsection, cost-resource curves for solar PV technologies have been estimated based on spatially explicit irradiation data. Three types of PV installations have been integrated into the analysis including plants mounted on free fields, plants mounted on the top of a roof and plants integrated into the building facade. The available floor area for all three types has been estimated based on a simplified approach. Thereby, the estimation of the land area feasible for the installation of free field PV plants based on the total agricultural land and a suitability factor is characterised by high uncertainties. In particular the determination of the suitability factor is not exempt from a certain degree of arbitrariness. It should be kept in mind that the overall PV potential for free-field plants in capacity terms is highly sensitive to the suitable surface area. With regard to the assessment of the area suitable for building-integrated PV power plants, the applied data is based on average calculations assuming facade and roof area per inhabitant. In this way, country specific differences in living space per inhabitant are not taken into account. Furthermore, potential future changes in the living space have not been taken into account. With regard to the composition of the roof types, the share of flat and pitched roofs in the roof area suitable for the construction of PV power plants was not considered as a result of lacking information on this issue.

Irradiation data, available for different inclination angles of the PV modules, has been used to create utilisation intervals on MS level. An important advantage of the applied radiation data consists in the high spatial resolution of 5 arc-minutes corresponding to a grid size of approximately 9.3 km * 9.3 km. In addition, irradiation data for different inclination angles, accounting for shadowing effects of the local terrain could be resorted to. Losses resulting from deviations from the optimal inclination angle in case of roof-integrated PV installations have been neglected. This simplification involves a slight overestimation of the feasible utilisation for roof-integrated PV power plants. In addition, it should be taken into account that differences in local conditions influencing e.g. the performance ratio differently throughout the EU have been neglected. This leads to an underestimation of the PV potential in Northern parts of Europe and to a slight overestimation in Southern Europe, where higher module temperature involve certain efficiency losses.

Instead of a direct map overlay of the geo-referenced data including the estimated area suitable for PV power plants and the respective radiation data, discrete utilisation intervals built for each country have been used to split up the estimated capacity potential. Thus, the fact that urban areas are not evenly distributed across a country is not accounted for in this analysis. Accordingly, this simplification reduces the accuracy of the results. Likewise it is probable that in case of free field solar PV plants a higher share of the agricultural floor area is dedicated to PV power plants in Southern parts of a country with more favourable weather conditions than areas with a less favourable solar regime. As a consequence the resulting costs of the cost-resource curves tend to be overestimated. Neither grid integration issues have been considered for the derivation of the cost-resource curves nor improvements of the conversion efficiencies in the long run.

4.4 Cost-resource curves for biomass technologies

Energy from biomass may contribute to mitigating climate change. However, the feedstock biomass tends to be utilised for various purposes besides the energetic use, such as food, animal feed and material use. This means, that the energetic use of biomass is exposed to competition with other uses of the feedstock itself, or for the area required to cultivate the corresponding feedstock[34]. In addition, the use of biomass may involve undesired environmental effects. As an example, an excessive removal of residual wood from the forests may pose a threat for the forest's biodiversity. When estimating the biomass potential available for energy purposes, these facts should be taken into account.

4.4.1 Biomass resources

A variety of different biomass resources can be used for the provision of electricity, heat or transport fuels. Each substance can be characterised by different attributes.

First, different biomass categories can be differentiated according to the material properties. Just to name but a few, these properties include the moisture content, the calorific value[35] and the cellulose/lignin ratio (McKendry 2002). Biomass feedstock with low moisture content (dry biomass) tends to me more suitable for thermal conversion processes; whilst biochemical processes require biomass with higher moisture content (wet biomass). In addition, the moisture content has an impact on the transportation costs of the

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34 For a detailed discussion of competition between biomass uses the reader is referred to 'Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen' [WBGU] 2009).

35 The calorific value describes the heat value that can be released by burning and represents a measure for the energy content of a feedstock.

biomass. As biodegradability of lignin is rather low, biomass with a high share of lignin such as wood is not suitable for the production of biogas via digestion.

Second, one can distinguish between biomass resources resulting from forests or from agriculture. The latter category includes e.g. cereals, sugar beets, oil seeds or short rotational crops. Besides the use of the final products from agricultural and forestry cultivation activities, different types of residual resources are available for energetic purposes. These include primary residues which are by-products directly available from biomass cultivation activities (thinnings from forests, straw, animal wastes, etc.). Secondary residues represent by-products emerging during any kind of biomass processing activity. For example black liquor, a by-product of pulp and paper production, represents a secondary biomass residual. Biomass, which has already been used such as the biogenic fraction of municipal waste or demolition wood, is generally referred to as tertiary residues.

Important input factors determining the potential resource availability of certain biomass feedstock are the availability of land that can be used for biomass crops, the land productivity and competition of energetic biomass use with material use and its use as food.

4.4.2 Biomass conversion technologies

Inside the energy sector, biomass feedstock may be used for various purposes, that is, for the production of heat, electricity or transport fuels. In general biomass can be converted into final energy by means of several technical processes including the direct combustion of the feedstock or a pre-processing such as gasification or digestion (cf. Figure 4-13). The main conversion pathways for the energetic use of biomas are described subsequently.

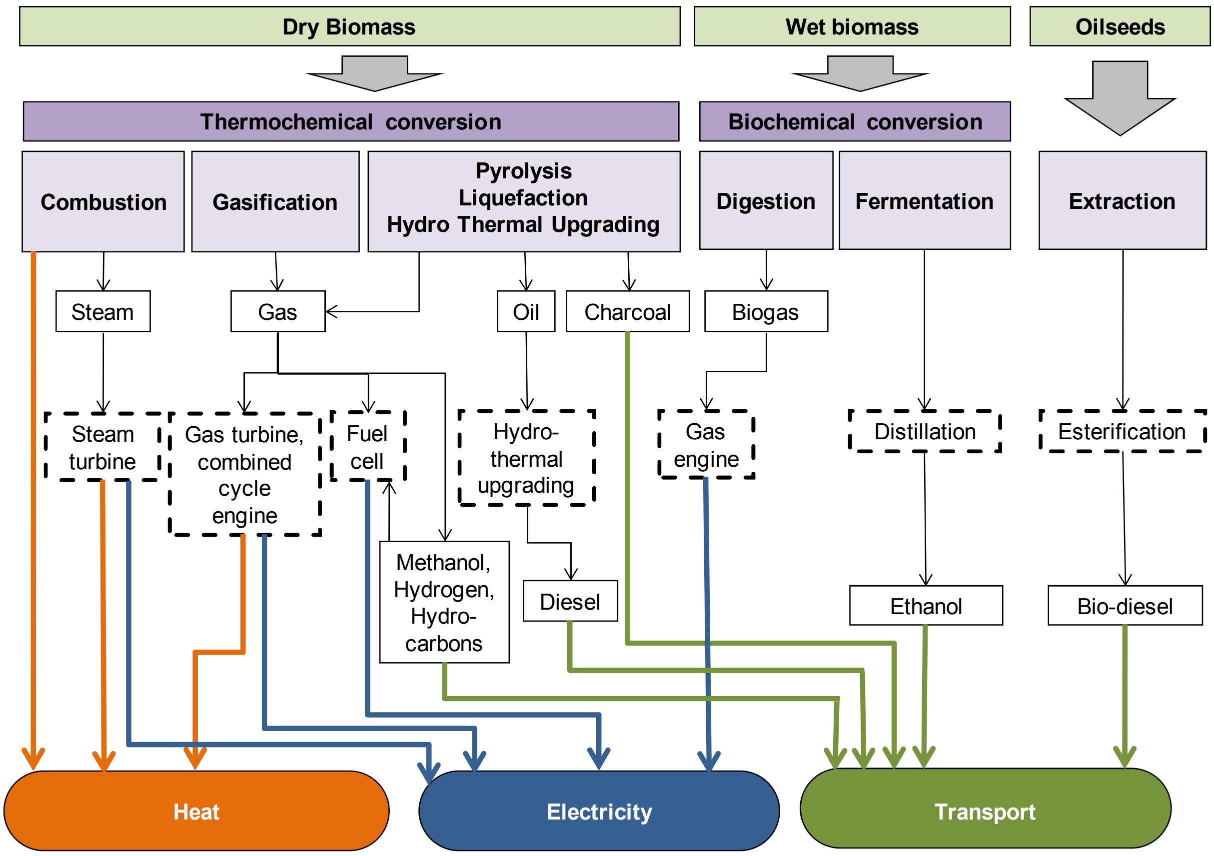

Figure 4-13 Main conversion pathways for the energetic use of biomass

Source: based on Turkenburg et al. (2000)

4.4.2.1 Combustion

Regarding biomass combustion, the biomass is incinerated directly either in heating plants, in pure electricity generation plants or in combined heat and power (CHP) plants. The applied systems may take the form either of small domestic systems using firewood or wood pellets or large centralised plants. Large centralised biomass combustion power plants mostly are cogeneration or CHP plants. These large cogeneration plants tend to be utilised in countries with a considerable biomass potential, in combination with a sufficiently high heating demand. In some cases, this heating demand occurs from industrial processes in energy-intensive industries. For example, large biomass conversion plants are often operated closed to pulp and paper production facilities, where black liquor, a by-product of the industrial process is utilised as fuel. Co-combustion of biomass in plants fired with conventional fuels such as coal is able to utilise biomass in existing conventional fuel power plants. This co-firing option represents a comparatively cost-effective option of reducing GHG emissions. At present, bio-energy plays the most important role in the heating sector. Whilst REN21 estimates the global heating capacity to 250 GW_{therm} in 2008, the totally installed electric capacity only amounts to 50 GW_{el} (Renewable Energy Policy Network for the 21st century [REN21] 2009).

4.4.2.2 Digestion

In an anaerobic digestion process, microorganisms decompose the biogenic feedstock in a humid environment in the absence of oxygen. Thereby biogas, consisting mainly of methane and carbon dioxide, evolves from this process. Subsequent to the digestion process, the biogas can be used in gas turbines or engines for electricity or CHP-production. Alternatively, the biogas can be fed into the gas distribution network after having passed an upgrading process, wherein the share of CO_2 is reduced and the biogas is converted into 'biomethane'. Anaerobic digestion for electricity production is characterised by a comparatively low electrical efficiencies ranging from 10 to 15 % depending on the feedstock utilised Faaij (2006a). In particular wet biomass resources such as manure, organic wastes or sewage sludge are well suited for anaerobic digestion. In contrast, ligno-cellulosic biomass can not be digested by bacteria in an anaerobic process.

In the modelling analysis, the following three categories of biogas technologies are distinguished according to the respective origin of the biogas:

- Biogas based on agricultural products such as manure, organic wastes and agricultural residues,
- Biogas originating from digestion at landfill sites,
- Biogas based on sewage sludge, which emerges e.g. during a waste water treatment process.

4.4.2.3 Other conversion options

Besides the described options of direct combustion and digestion, there are further options of using biomass feedstock for energetic purposes. In this way, solid biomass can be converted into combustible gas or syngas in a gasification process, where the solid fuel is dried and subsequently pyrolised at high temperatures[36]. Electrical conversion efficiencies range from 40 to 50 % like for example in combined-cycle plants (Biomass Integrated Combined Cycle – BIGCC). In addition, solid biomass that is not suitable for an anaerobic digestion process such as ligno-cellulosic biomass including wood and straw or by-products from anaerobic digestion can be used for gasification. Faaij (2006b) evaluates the BIGCC-technology to be still in its demonstration phase. One further technology choice for gasification of biomass represents the use of the produced gas in indirect co-firing plants.

Further liquid products (bio-oils) resulting from the pyrolisis process such as methanol and solid products such as charcoal can be used for energetic uses in the transport sector. These fuels, which originate from cellulosic or ligno-cellulosic biomass, are referred to as second generation biofuels. In addition, hydrogen can be extracted from the pyrolisis, if water steam is added during the process. First generation biofuels include biodiesel, which results from the extraction and production of esters from oilseeds and bioethanol, final product of sugar and starch fermentation.

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36 Pyrolisis can be understood as the chemical decomposition of organic material in the absence of oxygen and under high temperatures.

4.4.3 Europe's bioenergy potential – existing studies

Regarding bioenergy, the derivation of cost-resource curves is based on existing data on the available biomass potential. Several studies have been compared in order to select the most appropriate potential data. The potential data should ideally fulfil certain criteria including:

- Data availability on country level
- Preferably high disaggregation of feedstock
- Consideration of sustainability criteria
- Consideration up to 2050

The potential comparison shown in Figure 4-14 aims at indicating the magnitude of the different potential categories rather than to show exact potential figures due to the following reasons. The regional coverage of potential data differs slightly. Potentials partly were taken from global potential studies and are shown for Western Europe, including EU15, Turkey, Switzerland and Norway. Oonly the Western European part is shown in the comparison to compare these potentials with data from European studies. The potential definitions are of wide scope and potential determination depends strongly on the methodology applied and assumptions made. Different biomass resources were included into the analyses in case of the biomass potentials or data on certain biomass categories were missing on a regional disaggregated level.

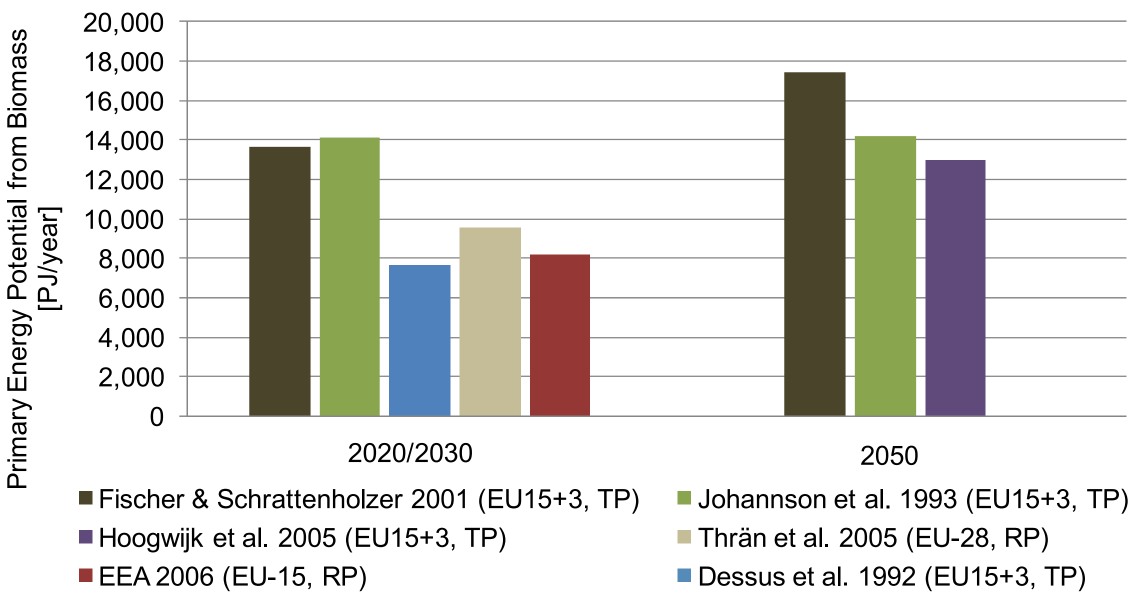

Figure 4-14 Comparison of the biomass primary energy potential in Europe. EU15+3 includes Norway, Switzerland and Turkey, TP means 'Technical Potential' and RP stands for 'Realisable Potential'

Fischer & Schrattenholzer (2001) estimated the Western European biomass potential consisting of energy crops and residues, wood and forest residues to 17,435 PJ by 2050 and to 13,635 PJ/year by 2020. The potential figures do not include bioenergy from animal waste and municipal waste. Potential calculations are based on a land-use model of IIASA and are supplemented with data from Dessus et al. (1992) for the bioenergy from wood products and residues. Assumptions about future food demand and supply are considered within the study. Neither country-specific data is available nor are all the important biomass resources (e.g. animal and municipal wastes) covered by this study.

The 'Renewables-intensive global energy scenario' (RIGES) predicts a primary energy potential from biomass resources for Western-Europe of 14,160 PJ/year by 2025 and of 14,170 PJ/year by 2050 (Johansson et al. 1993). Thereby, the biomass potential comprises resources from wood, energy crops, agricultural residues and industrial biomass residues. The estimations are based on the biomass production at that time in combination with specific assumptions on future growth rates. The study is characterised by missing data at national level and does not reflect the state-of the art, since knowledge about the use of bioenergy has been improving since 1993.

Hoogwijk et al. (2005) assume the biomass energy potential in Western Europe from energy crops, agricultural residues, forest residues and industrial biogenic residues to be in the order of 10,000 PJ/year and 16,000 PJ/year by 2050. The analysis is based on the IMAGE 2.2 model, using the four scenarios from the 'Special Report on Emissions Scenarios' (SRES) as main assumptions for the included food demand and supply (cf. Nakicenovic 2000). Hoogwijk et al. (2005) do not provide data at national level either.

Although Dessus et al. (1992) did not consider competition of energy crops with food production, the estimated bioenergy potential (wood, energy crops and waste) of 7,620 PJ/year by 2020 is lower than in the other studies considered for the respective time frame.

All the potential estimations described previously stem from global potential studies. Thus, the level of detail tends to be lower than in studies focussing exclusively on Europe. For this reason none of the described studies is considered for further analysis.

In a European potential study, Thrän et al. (2005) place the primary biomass potential at 9,550 PJ by 2020 for the EU27 plus Turkey assuming an environmental-friendly use of biomass. In case of a current policy scenario the potential increases to 14,750 PJ by 2020. As the time horizon of 2020 appears to be too short, this potential study was evaluated to be inappropriate for the purposes of PowerACE-ResInvest.

The study initiated by the European Environment Agency [EEA] (2006) aims at determining the environmentally-compatible bioenergy potential. That means that a number of environment criteria was selected and used as assumptions and restrictions for the potential calculations. Bioenergy crops, agricultural residues, forest products, forest residues and wastes of biological origin from agriculture, industry and households were included for the potential estimations. The estimated potential amounts to 7,394 PJ/year in 2020 and to 8,918 PJ/year in 2030. This value corresponds to about 50 to 60 % of the biomass potential calculated by Fischer & Schrattenholzer (2001) and Johannson et al. (1993) for the period between 2020 and 2030. This study is chosen as the basis for the calculation of the cost-resource curves due to the application of various sustainability criteria and a detailed consideration of a high number of different biomass resources, although it considers only a time horizon up to 2030.

Given that the development of the potentials from 2010 to 2030 (see Figure 4-15) appears to be nearly constant for biomass from forestry and wastes, it is assumed that the further development up to 2050 remains on a similar level. Potential increases in the agricultural potential up to 2050 are discarded.

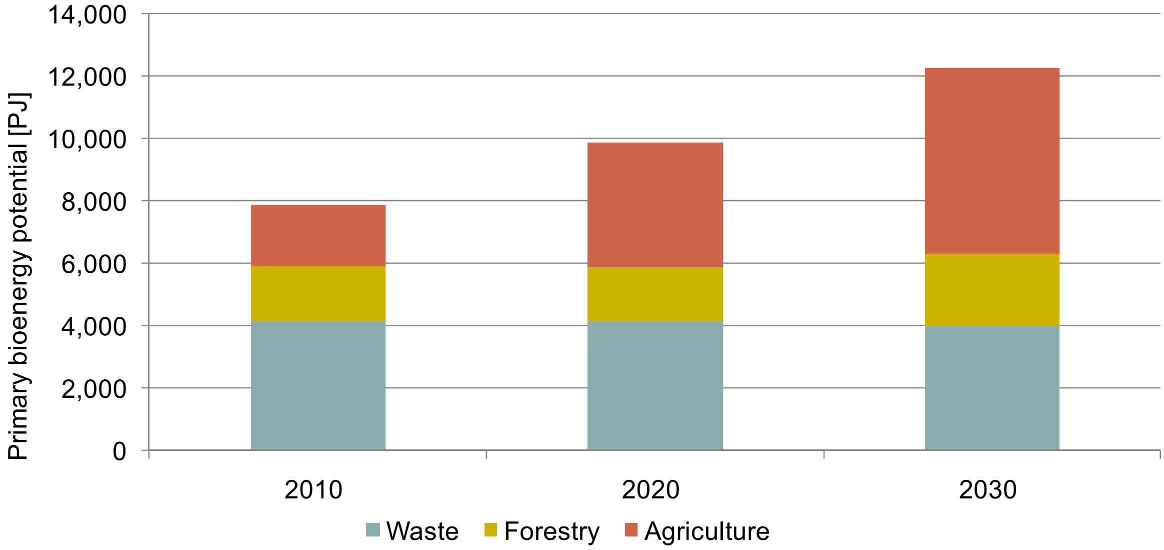

Figure 4-15 Environmentally-compatible bioenergy potential in EU25
Source: Based on European Environment Agency [EEA] (2006)

4.4.4 Allocation of resources to conversion technologies

In order to derive cost-resource curves for bioenergy, the available potential of the different biomass fuels is allocated to the appropriate conversion technologies. Thereby, one should consider that some of the biomass resources may be utilised alternatively in the sectors by different conversion technologies. Indeed, some conversion technologies can only make use of biomass resources with certain characteristics. In principle, the different conversion technologies should compete for the biomass resources. Thereby, it is difficult to find an adequate criterion suitable to compare the most appropriate process chain for the energetic use of biomass due to the heterogeneity of the final products electricity, heat and transport fuels. For example heat and electricity do not represent comparable quantities as electricity represents an energy form of a higher valence than heat due to its higher exergetic content[37]. In addition, the modelling realised in this study does neither cover the heating nor the transport sector. Therefore, it was decided to make a pre-allocation of the biomass energy carriers to the electricity sector based on expert judgements (see Table 4-6). The different technologies compete in the applied model for the biomass resources assumed to be available in the electricity sector (including CHP-plants).

Oil seeds such as rape and sunflowers are typically converted via esterification into biodiesel, wherefore it is assumed, that these crops are not available for electricity generation technologies. Likewise, grains of maize, wheat, barley or triticale are used for the production of biofuels by means of fermentation and are

[37] Exergy describes the ability of a system to produce work.

assumed not to be available for electricity production either. 20 % of the whole plant of barley, wheat and triticale is assumed to be utilised for direct combustion in the electricity sector, whilst 80 % are assigned to the production of 2nd generation biofuels in the long term up to 2050. Short rotational crops (SRC) and perennial grasses are allocated one half each to combustion in the electricity sector and to 2nd generation biofuels. Sweet sorghum can also be used for the production of bioethanol. Some of the agricultural products and residues are assumed to be at the disposal of the production of biogas via gasification or digestion. In these cases, a pre-conversion of the primary biomass feedstock is required involving certain efficiency losses. According to data from Oekoinstitut (2006) the respective efficiencies of 70 % for the anaerobic digestion process and of 92 – 95 % for the gasification process are applied for the pre-conversion. These efficiencies consider expected technical improvements up to 2030. Most of the available manure potential is expected to be applied in combination with an anaerobic digestion process. The main part of woody biomass is supposed to be used in the heating sector (see Table 4-6).

Table 4-6 Assumptions for the share of biomass primary energy available for the electricity sector

		Sector/Technology					
		Electricity/CHP		Heat	Transport		
Resource category	Biomass resources	Com-bustion	Digestion/ Gasi-fication		Diesel	Ethanol	2nd genera-tion fuel
Agricultural products (AP)	Oil seeds: rape & sunflower				100%		
	Maize, wheat, barley, triticale (grain)					100%	
	Maize, barley, wheat, triticale (whole plant)	20%					80%
	SRC (poplar, willow, miscanthus, reed canary grass, giant reed, sweet sorghum), perennial grasses	50%					50%
	Switch grass, double cropping systems, grass cutting from permanent grass land	30%	70%				
Agricultural residues (AR) / agricultural biogas (ABG)	Food processing wastes - dairy/sugar industry, wine and beer production	70%					
	Solid agricultural residues - cereal and rapeseeed straw, stalks from sunflowers and prunings from vineyards and olive trees, green tops from potatoes and beets	70%	15%				
Agricultural biogas (ABG)	Manure from cows, pigs and laying hens (wet)		100%				
	Manure from fattening hens (dry)		100%				
Biowaste (BW)	Biogenic fraction of municipal solid waste - Incineration	80%					
Landfill gas (LG)	Biogenic fraction of municipal solid waste - Composted		80%				
	Biogenic fraction of Municipal solid waste - Landfilled		100%				
Sewage sludge (SG)	Sewage Sludge		100%				
Forestry products (FP)	Forestry products (wood chips, logwood)	40%		60%			
Forestry residues (FR)	Direct forestry residues	25%		75%			
	Wood-processing waste wood - sawdust & offcuts from primary (sawmills) and secondary (furniture manifacture) wood processing	25%		75%			
	Construction/ Demolition Wood	25%		75%			
	Packaging Waste Wood	25%		75%			
	Household Waste Wood	25%		75%			
Black liquor (BL)	Black liquor	25%		75%			

Source: Own illustration. Allocation to technologies based on information from European Environment Agency [EEA] 2008, pp. 73 – 74)

In the next step, the primary resource potentials as shown in Table 4-6 are used to derive final energy potentials based on the efficiencies of electricity generation technologies, as specified in Table 4-7. Finally, the inclusion of economic parameter (see Table 4-7) of conversion technologies finalises the creation of cost-resources curves. Assumptions on the development of primary fuel prices are based on a database created by the Energy Economics Group of the University of Vienna in the context of the FORRES2020 project (Ragwitz et al. 2005b).

Table 4-7 Technical and economic characteristics of biomass conversion technologies considered for the determination of the cost-resource curves

			Investment	**O&M costs**	**Electric Efficiency**	**Heat efficiency**	**Life-time**	**Typical plant size**
Technology	**Plant type**	**Feed-stock**	*[€/kW$_{el}$]*	*[€/ (kW$_{el}$*a)]*			*[a]*	*[MW$_{el}$]*
Biogas	Agricultural biogas plant	ABG	2,550 – 4,290	115 - 140	0.28 - 0.34	-	25	0.1 - 0.5
	Agricultaral biogas plant – CHP	ABG	2,760 – 4,500	120 - 145	0.27 - 0.33	0.55 - 0.59	25	0.1 - 0.5
	Landfill gas plant	LG	1,280 – 1,840	50 - 80	0.32 - 0.36	-	25	0.75 - 8
	Landfill gas plant – CHP	LG	1,430 – 1,990	55 - 85	0.31 - 0.35	0.5 - 0.54	25	0.75 - 8
	Sewage gas plant	SG	2,300 - 3400	115 - 165	0.28 - 0.32	-	25	0.1 - 0.6
	Sewage gas plant – CHP	SG	2,400 – 3,550	125 - 175	0.26 - 0.3	0.54 - 0.58	25	0.1 - 0.6
Biomass	Biomass plant	AP, AR, FP, FR, BL	2,225 – 2,530	75 - 135	0.26 - 0.3	-	30	1 - 25
	Cofiring	AP, AR, FP, FR	550	60	0.37	-	30	-
	Biomass plant – CHP	AP, AR, FP, FR, BL	2,600 – 4,230	80 - 165	0.22 - 0.27	0.63 - 0.66	30	1 - 25
	Cofiring – CHP	AP, AR, FP, FR	550	60	0.2	0.6	30	-
Biowaste	Incineration plant	BW	4,300 – 5,820	90 - 165	0.18 - 0.22	-	30	2 - 50
	Incineration plant – CHP	BW	4,600 – 6,130	100 - 185	0.14 - 0.16	0.64 - 0.66	30	2 - 50

Source: Data based on Ragwitz & Resch (2006)

Observing the final cost-resource curves shown in Figure 4-16, it becomes clear, that the potential of biowaste combustion amounting to nearly 0.5 TWh results to be considerably lower than that of biogas technologies or incineration plants fed with other solid biomass resources than biowaste. Depending on various characteristics such as plant size, fuel cost or the conversion technology, electricity generation costs of biomass conversion technologies show a broad range, starting from less than 20 €/MWh in case of landfill gas power plants up to 270 €/MWh in small-scale solid biomass incineration plants which use comparatively expensive feedstock such as agricultural or forestry products. It should be observed that the low-cost potential of e.g. landfill gas fired plants is limited.

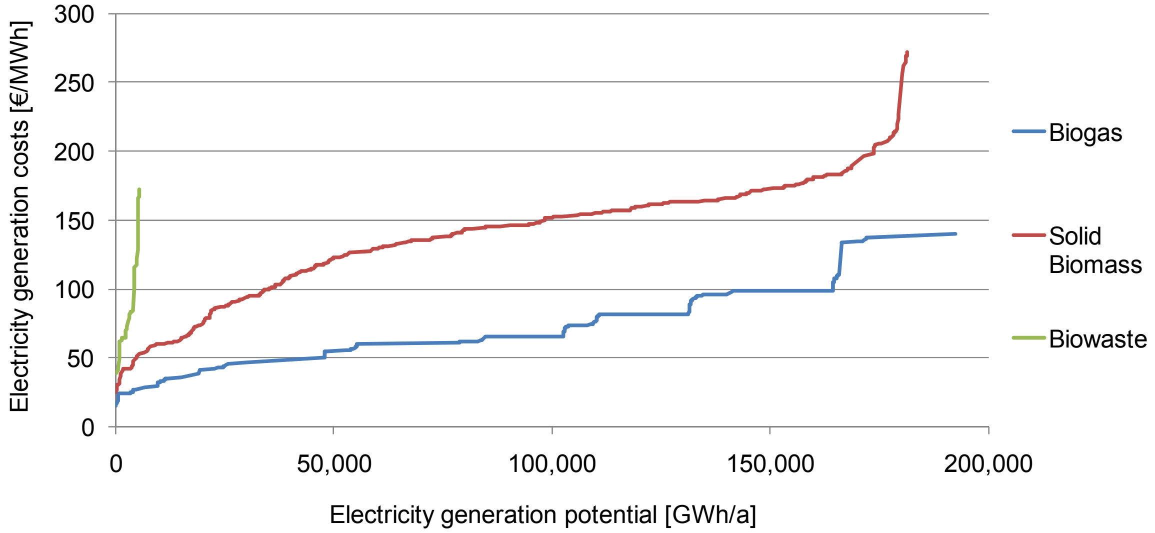

Figure 4-16 Derived cost-resource curves for biomass conversion technologies in the EU27 for 2009
Source: Own calculations

4.4.5 Learning rates

Given the large variety of biomass conversion options available, potential cost reductions of biomass conversion technologies are difficult to estimate. Existing estimations from literature indicate a potential reduction by 3 - 25 % in the investment with each cumulative doubling of the capacity installed (see Table 4-3). Thereby, Junginger et al. (2006) identify learning-by-using and learning-by-interacting as important driving factors for small-scale applications, whilst large-scale CHP plants apparently benefit from increased plant sizes.

Table 4-8 Overview of exemplary learning rates for biomass conversion technologies

Technology	**Geographical coverage**	**Time frame**	**Learning rate [%]**	**Cost indicator**	**Experience indicator**	**Author**
CHP biomass power plant	Sweden	1990-2002	3-25	Investment	Cumulative capacity	Junginger et al. (2006)
			8-9	Electricity generation costs	Cumulative capacity	
Biogas plants	Denmark	1984-2002	12	Investment	Cumulative capacity	Junginger et al. (2006)
Biomass power plant	EU	1980-1995	15	Electricity generation costs	Cumulative electricity production	International Energy Agency [IEA] 2000
Biomass integrated gasification/ combined cycle (BIGCC)	Global	Modelling assumption	7 - 9	Investment	Cumulative capacity	Uyterlinde et al. (2006)

4.4.6 Discussion of results

The derivation of cost-resource curves has been based on a potential estimation available in literature.The primary potential assessed by the European Environment Agency until the year 2030 is based on assumptions aiming at an environmentally-compatible use of biomass (European Environment Agency 2006). One critical issue of the derivation of cost-resource curves for biomass electricity represents the fixed allocation of biomass resources to the end use sectors electricity, heat and transport and subsequently to the individual conversion technologies. In order to depict this situation more realistically, an inclusion of the heat and transport sector into the simulation model would be required. Though, this issue goes beyond the scope of this thesis. In the area of energetic biomass use, the distance between the location of biomass production and the corresponding conversion technologies may be important in particular in case of wet biomass resources due to costs of transportation. This aspect could not be accounted for in this analysis either.

4.5 Cost-resource curves for other renewable energy technologies

For other RES conversion technologies such as concentrating solar power (CSP), offshore wind, hydropower, marine energy and geothermal energy, the derivation of cost-resource curves is realised based on data available in literature. Similar to the derivation of regional cost-resource curves for onshore wind and PV, a more detailed derivation of regional cost-resource curves for CSP and offshore wind would be feasible improve data quality. With respect to geothermal energy and marine energy, the theoretical potential is vast, but due to uncertainties regarding the respective conversion technologies, the precise estimation of the realisable potential remains difficult. Looking at the realisable potential for hydropower, only little additional potential is available for the construction of new plants.

4.5.1 Concentrating solar power

In case of solar thermal electricity power plants, direct solar irradiation is bundled by a solar collector and converted into thermal energy. Via a heat carrier the thermal energy is converted into work and finally into electrical energy using conventional heat engines (steam turbines, Stirling engines). Solar thermal power plants can be distinguished according to their system design.

In case of parabolic trough plants the sunlight is concentrated by parabolic reflectors before the heat carrier is generally used in a conventional steam turbine. A solar power tower consists of a field of flexible mirrors focusing the sunlight upon a receiver installed on a central tower. The Dish/Stirling engine consists of a large parabolic dish that concentrates the sunlight. Commonly, the dish is combined with a Stirling engine. Compared to parabolic trough and the power tower design, the Dish/Stirling engine facilitates the installation of smaller units (Quaschning 2008, p. 172).

In contrast to wind power or solar PV plants, the solar thermal technology enables to store the thermal energy in molten salt storage, compressed air storage or latent heat storage and improves therewith the dispatchability of solar thermal electricity.

Cost-resource curves for solar thermal electricity have been derived based on an estimation for the realisable potential by 2020 from (Ragwitz & Resch 2006). In order to account for the fact that cost-resource curves should include the realisable potential by 2050, it was estimated to amount twice the realisable potential estimated for the year 2020. Thus, the total realisable potential for solar thermal electricity is estimated to amount to roughly 60 TWh a year. Cost-resource curves have been derived based on the economic parameters shown in Table 4-9.

Table 4-9 Technical and economic characteristics of solar thermal electricity technologies considered for the determination of the cost-resource curves

	Investment	**O&M costs**	**Life-time**	**Typical plant size**
Technology	*[€/kW$_{el}$]*	*[€/ (kW$_{el}$*a)]*	*[a]*	*[MW$_{el}$]*
Concentrating Solar Power (CSP)	2,880 – 4,465	163 - 228	30	2 - 100

Source: (Ragwitz & Resch 2006)

With a view to potential future cost reductions Jamasb (2007) placed the learning rate for solar thermal power at 22.5 %, as shown in Table 4-10.

Table 4-10 Exemplary learning rates for concentrating solar power plants (CSP)

Technology	**Geo-graphical coverage**	**Time frame**	**Learning rate [%]**	**Cost indica-tor**	**Experience indicator**	**Author**
CSP-plant	Global	1985-2001	22.5	Investment	Cumulative capacity	Jamasb (2007)

4.5.2 Wind offshore

As specified in section 4.2, electricity produced with wind turbines installed offshore originates from the wind's kinetic power. In contrast to onshore wind energy, offshore wind power plants are typically characterised by more favourable wind regimes. This means, that local wind speeds are generally higher than in case of onshore and tend to be more evenly distributed. However, investment requirements are generally higher than in case of onshore wind. The economic performance of offshore wind power plants depends in particular on the water depth, the distance to shore and the local wind regime.

Owing to limited data availability on the realisable potential for offshore wind electricity by 2050, different data sources are used to derive the respective cost-resource curves. For EU15 countries a future scenario of offshore wind electricity generation up to 2020, published by Greenpeace, serves as input for the determination of cost-resource curves (cf. Snodin 2004, p. 21). Since the study's indication for the offshore wind potential in Germany of roughly 12 GW appears to be rather low the offshore wind potential data is adapted to 30 GW based on information from Deutsche Energie-Agentur [DENA] (2005, p. 59). In order to derive cost-resource curves for the remaining MS of the EU estimates for the realisable potential by 2020 are used (Ragwitz & Resch 2006). Taking into account several adaptations of the available data, a total offshore wind potential amounting to 252 GW and 845 TWh for the EU as a whole is assumed for the derivation of cost-resource curves. In general, the investment for a offshore wind power plant depends on the water depth and the distance to shore. The economic characteristics assumed for the calculation of the cost-resource curves are depicted in Table 4-12.

Table 4-11 Technical and economic characteristics of offshore wind technologies considered for the determination of the cost-resource curves

	Investment	**O&M costs**	**Life-time**	**Typical plant size**
Technology	*[€/kW$_{el}$]*	*[€/ (kW$_{el}$*a)]*	*[a]*	*[MW$_{el}$]*
Wind Offshore	1,700 – 2,500	57 – 68	20	5

Source: Based on European Environment Agency [EEA] (2009, p. 38); Ragwitz & Resch (2006)

Due to less experience with the installation of wind power plants offshore the derivation of learning curves becomes more difficult than in case of onshore wind power plants. Existing studies in literature suggest learning rates in the order of 5 – 9 % (see Table 4-12).

Table 4-12 Exemplary learning rates for offshore wind energy

Technology	**Geographical coverage**	**Time frame**	**Learning rate [%]**	**Cost indicator**	**Experience indicator**	**Author**
Wind offshore	Global	Modelling assumptions	5 – 9 (only turbine)	Investment	Cumulative capacity	Junginger et al. (2004) Uyterlinde et al. (2007)
		1994-2001	8.3	Investment	Cumulative capacity	Jamasb (2007)

4.5.3 Hydropower

In hydropower plants the potential energy stored within water available at a certain elevation level is converted into kinetic energy at first. A turbine then transforms the kinetic energy into mechanical energy, utilised in turn by a generator in order to produce electricity. The amount of electricity produced depends on the discharge quantity on the one hand and the hydraulic head on the other hand. Depending on these two factors different types of water turbine are employed. Kaplan turbines are well-suited for low-head and high-flow conditions and are typically applied in power plants located on large rives. In case of medium hydraulic heads of up to 700 m and medium flow conditions, Francis turbines represent the preferred turbine design, whereas Pelton turbines are generally applied in mountainous terrains with high hydraulic heads and low flows (Quaschning 2008, p. 217 - 218). By using water turbines, high conversion efficiencies ranging from 80 – 90 % can be obtained.

Furthermore, hydropower plants can be distinguished according to their construction design. In case of **run-of-the-river hydropower plants** no storage capacity is available whereas **storage hydropower plants** dispose of a barrage, which can be used to store the water in times of low electricity demand. With rising electricity demand locks are opened and electricity production starts again. If the hydropower plant is equipped with additional pumps, this technology is referred to as a **pumped-storage hydropower plant**. With hydropower pumped-storage power plants surplus electricity can be used in off-peak periods to pump the water from the lower to the higher elevation level. The pumped-storage hydropower plant requires an additional water reservoir at the lower elevation level. Pumped-storage hydropower plants are characterised by efficiencies ranging between 70 and 80 % (Quaschning 2008, p. 223). Thus, pumped-storage hydropower plants are well-suited to balance load fluctuations, originating e.g. from an increased feed-in of variable wind electricity.

Aspects of electricity storage are however not considered for the potential estimation of future hydropower exploitation. This means that in case of pumped-storage hydropower plants with a natural water inflow, only the original electricity generation capacity is accounted for. The pumped-storage capacity is not considered, as the electricity generated after pumping is originally produced in other installations and would involve double-counting.

In this analysis, hydropower plants are distinguished according to their capacity size into small-scale hydropower plants with a capacity of up to 10 MW and large-scale installations with a capacity exceeding 10 MW.

Cost-resource curves for the remaining hydropower potential in European countries are based on a estimation of the realisable potential by 2020 published by (Ragwitz & Resch 2006). A large share of the European hydropower capacity potential is already being exploited in particular with regard to large-scale power plants. Therefore, the overall large-scale hydropower potential by 2050 is assumed to correspond to the 2020 potential amounting to 364 TWh per year. In case of small-scale hydropower, the 2020 potential is multiplied with an interpolation factor of 1.2 corresponding to a small-scale hydropower potential of about 79 TWh per year. The derivation of cost-resource curves is based on assumptions on the economic parameters represented in Table 4-13.

Table 4-13 Technical and economic characteristics of hydropower plants considered for the determination of the cost-resource curves

		Investment	**O&M costs**	**Life-time**	**Typical plant size**
Technology	**Plant specification**	*[€/kW$_{el}$]*	*[€/ (kW$_{el}$*a)]*	*[a]*	*[MW$_{el}$]*
Small-scale hydropower	New plant	5,000 – 7,700	40	50	0.3 – 10
	Refurbishment	2,000 – 3,070	40	50	0.3 – 10
Large-scale hydropower	New plant	3,650 – 5,000	35	50	20 – 250
	Refurbishment	1,000 – 2,000	35	50	20 – 250

Source: Based on Ragwitz & Resch (2006) and Staiß (2007)

Given the technological maturity of hydropower plants, learning rates of hydropower appear to be rather low. In this way, Jamasb (2007) estimated learning rates for hydropower plants to amount to roughly 3 % (see Table 4-14).

Table 4-14 Exemplary learning rates for hydropower plants

Technology	Geographical coverage	Time frame	Learning rate [%]	Cost indicator	Experience indicator	Author
Large hydropower	Global	1980-2001	2.9	Investment	Cumulative capacity	Jamasb (2007)
Small hydro-power			2.8			

4.5.4 Marine power

Marine energy conversion technologies target to harness the energy contained in the oceans either in terms of waves, (tidal) currents, temperature differences between deep and shallow waters or salinity gradients between seawater and freshwater from rivers. The overall technical potential for the use of ocean energy is vast (Ragwitz et al. 2005a, p. 47), but the technology options to exploit the ocean's energy are still in a development or demonstration phase. Thus, Ragwitz et al. (2005, p. 48) characterise the state of the art of tidal barrage energy technologies as a technology in its commercial stage without being economically competitive, wave energy technologies as a technology being in its demonstration stage and salinity power plants as well as ocean thermal energy conversion (OTEC) to be still under development. Therefore, only marine energy technologies based on fluid flows – wave and tidal energy – are considered for this analysis.

In case of **tidal and marine current power** the energy contained in tidal streams is converted via mechanical energy into electrical energy. A **barrage tidal power plant** may consist of a barrage with sluices separating a basin from the sea. Water flows through turbines either from the basin to the sea or the other way around as a result of changing tides and the bi-directional turbines drive in turn a generator to produce electricity. In general, tidal barrage power plants allow for the operation in pumping mode in peak-load times. Thereby, minimum tidal ranges of 3 – 5 m are required. However, tidal barrages can involve considerable environmental impacts on the ecosystem of the bay or basin. The most prominent tidal barrage power plant in Europe "La Rance" started operation in 1966 and consists of 24 Kaplan turbines with a total capacity amounting to 240 MW (Quaschning 2007,p. 284). Another technical option of exploiting tidal streams or other currents of the sea represents **tidal stream power** or marine current power, where turbines similar to offshore wind turbines are installed in areas with tides or currents to produce electricity. Electricity produced in tidal power plants fluctuates according to tidal movement, but it is very predictable.

Wave energy converters intend to capture the energy of waves. There are alternative design options of the converters including buoyant moored devices, oscillating water columns (OWC) or overtopping devices. Buoyant moored devices transfer the movement waves to a electromechanical or hydraulic energy converters (Quaschning 2007, p. 224). In case of the OWC, air in a hollow structure upon the surface of waves oscillates following the motion of the waves and drives a turbine. Overtopping devices are composed of a wall-separated basin, where waves are caught. The water pouring out again into the sea then drives a turbine. The world's first commercial wave power farm 'Aguçadoura Wave Park' started operation in 2008 at the Portuguese Atlantic coast. It is composed of three 750 kW wave energy converters of the type buoyant moored devices. The so-called attenuators are long cylindrical floating devices oriented in parallel with wave direction. Wave-induced movements are constrained by hydraulic rams in order to produce electricity. However, the wave park experienced serious technical and financial problems and has been taken offline.

Estimating the realisable potential for the utilisation of marine energy involves a high degree of uncertainty due to the early stage of development of the corresponding conversion technologies. Similar to the case of hydropower, cost-resource curves applied in the model are based on the potential realisable until 2020 estimated by Ragwitz & Resch (2006). According to authors the realisable marine energy potential until 2020 amounts to 124 TWh per year. Given the existing uncertainties regarding the potential estimation, it was decided not to project the potential estimations to the year 2050.

Table 4-15 Technical and economic characteristics of marine power plants considered for the determination of the cost-resource curves

	Investment	**O&M costs**	**Life-time**	**Typical plant size**
Technology	*[€/kW$_{el}$]*	*[€/ (kW$_{el}$*a)]*	*[a]*	*[MW$_{el}$]*
Tidal power plant (barrage or stream)	2,670 – 3,025	44 - 53	25	0.5 - 2
Wave power plant	2,135 – 2,850	44 - 53	25	0.5 - 2

Source: Ragwitz & Resch (2006)

Given the little practical experiences with marine power technologies, learning rates have not been quantified based on time series so far. Table 4-16 shows estimations of learning rates derived combining engineering analysis and experiences from other industries.

Table 4-16 Exemplary learning rates for wave and tidal power plants

Technology	**Geographical coverage**	**Time frame**	**Learning rate [%]**	**Cost indicator**	**Experience indicator**	**Author**
Tidal stream energy	Estimation	-	5-10	-	-	The Carbon Trust (2006, p. 2)
Wave energy			10-15			

4.5.5 Geothermal power

In geothermal power plants, the energy stored in terms of heat in the earth is utilised to produce electricity via a thermodynamic cycle. Depending on the temperature gradient of the geothermal deposit, geothermal energy can be converted either into heat or electricity. In case of high enthalpy deposits, geothermal fluids of a temperature ranging from 150°C to 350°C may be used directly for electricity production in a steam turbine. This technology option is referred to as **hydrothermal geothermal power**. The required deposits can only be found in a restricted number of areas, such as in volcanically active zones. **Enhanced Geothermal Systems** (EGS) can be applied in order to utilise the heat of fluid-deficient resources. Thus, heat can be extracted from the underground by injecting fluids at high pressures by means of the **Hot-Dry-Rock (HDR)** technology. However, one HDR-project in Basel/Switzerland was stopped due to the presumption, that this project had caused an earthquake in the respective area. Medium enthalpy deposits with a temperature level ranging from 90 °C to 150 °C can be used in **binary fluid cycle power plants**. Thereby, the heat from the water is transformed via a heat exchanger to a fluid vaporising at lower temperatures followed by an Organic-Rankine-Cycle (ORC) or a Kalina process. The Organic-Rankine-Cycle uses organic fluids characterised by a boiling point below that of water for the operation of a steam turbine. Likewise, the Kalina process is based on an ammonia-water mixture and it is characterised by higher efficiencies than the ORC. However, the Kalina process is still situated in an early stage of technological development.

Generally, the electricity output of geothermal power plants is not subject to weather-induced fluctuations. Similar to the case of marine energy, the realisable potential until 2020 placed by Ragwitz & Resch (2006) at 3.8 TWh per year represents the basis for the cost-resource curves used for the simulation model. The corresponding economic parameters are shown in Table 4-17. Although there is the option of waste heat utilisation in geothermal power plants, only pure power generation plants are taken into account as technology option for the simulation model.

Table 4-17 Technical and economic characteristics of geothermal power plants considered for the determination of the cost-resource curves

	Investment	**O&M costs**	**Electric efficiency**	**Heat efficiency**	**Life-time**	**Typical plant size**
Technology	*[€/kW$_{el}$]*	*[€/ (kW$_{el}$*a)]*			*[a]*	*[MW$_{el}$]*
Geothermal electricity	2,000 – 3,500	100 - 170	0.11 - 0.14	-	30	2 - 50

Source: Based on Ragwitz & Resch (2006)

In case of geothermal use for electricity generation only moderate cost reductions can be expected. To the knowledge of the author no studies on the determination of learning rates for geothermal energy are available. Therefore, learning rates assumed in other energy models, ranging e.g. from 5 to 8 %, are used for comparison (Gumerman & Marnay 2004; Ragwitz & Resch 2006).

4.6 Summary and discussion

This chapter provided an overview of the techno-economic characterisation of RET in the electricity sector including the combination of available resource potential and the associated electricity generation costs, referred to as cost-resource curves. On the basis of a literature review regarding renewable potentials and cost-resource curves for selected technologies, the chapter showed that additional research was required to derive cost-resource curves adapted to the specific requirements of the simulation model. This includes the consideration of the modelling time horizon up to 2050 and a preferably high level of detail regarding all available RES and the respective technology options at least on country level. Therefore, cost-resource curves based on spatially explicit data have been derived for onshore wind and solar PV power plants. Regarding the consideration of weather-related data such as wind speed and solar irradiation, it should be considered that annual averages have been applied in the analysis. Thus, the low temporally resolution represents one main limitation of the applied approach. In case of biomass, a pre-allocation of different biomass feedstock, taken from an estimation of the primary biomass potential available in literature to conversion technologies, was realised using a top-down approach. Likewise, cost-resource curves for the remaining RES have been derived based on potential estimations available in literature. For all RES, dynamic developments of the investment over time were taken into account. Restrictions resulting from the fluctuating electricity output of some RET have not been considered.

5 Development of the simulation model PowerACE-ResInvest

Based on the identification of a suitable modelling approach to analyse the technology diffusion of RET as described in section 3.4, an ABS model is developed. The simulation model depicts the diffusion of RET in the electricity sector as a result of decentralised decision making processes. Heterogeneous agents such as investment planner agents face investment decisions for renewable energy projects and national governments shape the financial support conditions for investments in these technologies. The investment planner agents feature different characteristics and make some of their decisions based on heuristics instead of utilising optimising algorithms. National government agents are distinguished according to the primary support scheme they apply to achieve their individual renewable energy targets. In addition, the model enables a first quantitative assessment of new policy elements as implemented in Directive 2009/28/EC. These new policy elements are known as flexibility mechanisms and intend to stimulate a preferably cost-effective development of RET by enabling international cooperation mechanisms (see 2.1.4.1). The developed simulation model PowerACE-ResInvest is able to analyse how the heterogeneity of investment planner agents, their specific behaviour and the support mechanisms influence the diffusion of RET. Besides this, the question of how the agents' structure influence different policy options is addressed.

Even though the aim is to depict the main drivers of a future RET development as realistically as possible, certain phenomena in particular regarding the agents' population and behaviour are not empirically supported due to missing data availability. Instead, assumptions are made to investigate the agents' behaviour and their reactions towards a certain development of their environment. Detailed cost-resource curves derived in this analysis are integrated into the simulation model to integrate given restrictions determined by the available renewable potentials, the corresponding techno-economic characterisation of RES and the technological conversion options. These cost-resource curves are then adapted in order to be utilised in the context of a multi-agent problem (see section 5.5.5).

The integrated representation of diffusion processes for RET from an agent's perspective taking into account spatially explicit cost-resource curves adapted to the requirements of a multi-agent model and the current policy framework represents the core novelty of the thesis at hand.

5.1 Starting point

The simulation model developed within this thesis builds on a module of the existing model PowerACE, a model that the Fraunhofer Institute for Systems and Innovation Research and the University of Karlsruhe have originally developed on behalf of the 'Volkswagen Stiftung' (cf. Genoese et al. 2007b; Sensfuss 2008; Weidlich 2008)[38]. PowerACE simulates the German electricity sector and its markets from an agent-based perspective. The model is divided in four main categories, whereof the first is deal-

38 For more detailed information about the research project PowerACE, the reader is referred to http://www.powerace.de/.

ing with markets, the second with electricity demand, the third with utilities and the last one with renewable electricity generation. Regarding the markets, the model simulates a spot market for electricity, a market for balancing power and one for CO_2 emissions. The main agents represent consumers, utilities, agents for renewable energy, grid operators, government agents and market operators. The starting point for the developed simulation model PowerACE-ResInvest initially was a renewable investment module of PowerACE, which simulated the diffusion of onshore wind energy in Germany until 2020 (Sensfuss 2008, p. 164 - 171). In its original version, this module depicted uniform investment decisions based on net present value calculations considering limitations from plant manufacturing capacity and authorisation constraints.

Applying these basic mechanisms in the further development of the module, the author of this thesis realised substantial changes to the original approach including the implementation of fundamentally new aspects. These aspects comprise

- the extension of the spatial scope from Germany to Europe,
- the integration of RET others than onshore wind including CHP-technologies,
- the introduction of heterogeneous investment agents and policy agents,
- the adaptation of the cost-resource curves to requirements of a multi-agent framework,
- the integration of technological learning,
- the consideration of substitution decisions of existing power plants,
- the representation of a quota obligation scheme,
- the representation of potential price building mechanisms for statistical transfers,
- and the representation of climate change impacts on hydropower generation.

The technical implementation of the developed simulation model was exclusively realised by the author using the programming language Java. The amplification of the modelling horizon with regard to the spatial and the technological scope involved a complete reorganisation of the simulation procedure due to the introduction of additional dimensions in terms of countries and technologies. The reason for having selected this programming language and a short description of the practical implementation of the simulation model follows in the subsequent section.

5.2 Technical implementation

In its current version PowerACE-ResInvest runs independently from the rest of the electricity market simulation module PowerACE, as the latter one focuses on short-term effects and on the German market. Given existing similarities between agents in multi-agent systems and objects in object-oriented programming (OOP), the model is technically implemented using the OOP language Java. In particular the core concept of OOP, where autonomous objects consisting of various attributes and procedures interact, was judged to be well suited for the implementation of an ABS model. Objects represent particular entities of abstract concepts, which are initially defined in classes. This means that objects assume specific values for the abstract characteristics and behaviour predetermined by classes.

Other main features of OOP style support the selection of an OOP language for the implementation of an ABS model. This includes the *inheritance* of attributes and methods from classes to sub-classes and the *encapsulation* of objects, meaning that implementation details are hidden behind an interface (cf. Pierce 2002, p. 226 - 227). Finally, *(subtype) polymorphism* enables type-specific behaviour of objects if a method of the same name is called by overriding the inherited methods (cf. Pierce 2002, p. 226 - 227). The integrated development environment (IDE) Eclipse was used to support the Java development. Besides this, no additional software tools have been applied for model development.

In order to realise scenario runs using different sets of input data, scenario settings are managed in Extensible Markup Language (XML) files. The required input data for the model is handled based on the database system MySQL. Depending on the scenario settings different input database tables are read and used to parameterise different variables, fields and objects of the model. To give an example, a change in the policy setting regarding for example the level of the FIT available requires the creation of databases specifying the tariff for each year, technology and country. Assuming the disaggregation level used in PowerACE-ResInvest corresponding to 14 technologies, 27 countries and a simulation period of 45 years, this implies that 17,010 data entries have to be adjusted in order to change only the tariff level. Thus, suggested by the volume of input data required, a Visual Basic macro converting data from excel spreadsheets into the required database format has been developed in order to facilitate and to speed up the provision of scenario-specific input data or other data that has to be actualised regularly. One main component of this macro is a template, which specifies the format of the input and the output data structure. The macro comprises a template allowing for the adjustment to different data format requirements of input and output data. Additionally, data from several sheets can be exported to the MySQL database and stored in different database table in one step.

Looking at the evaluation of simulation results, model outputs are generated and processed in terms of comma-separated-value (csv) files. Data output is organised following a database structure, allowing for an easy and dynamic aggregation according to different criteria with pivot tables in Microsoft Excel. The schematic structure of the output is shown exemplarily in Table 5-1.

Table 5-1 Schematic example of data output format produced with PowerACE-ResInvest

Identifier 1	**Identifier 2**	**Identifier 3**	**Variable 1**	**Variable 2**
Year	*Country*	*Technology*	*Additional RES capacity [MW]*	*Investment [Million €]*
2006	Austria	Wind Onshore	50	64
2006	Belgium	Wind Onshore	60	77

Source: Own illustration

As shown in Table 5-2, the modelling output is organised in different categories characterised by a different level of details. For each of these categories a separate csv-file is created. To place an example, information of the government agents show data aggregated on country level, whilst very detailed data including information on each potential step of the cost-resource curve is stored in the category dealing with balancing of potential data. Due to high detail the latter category produces large amounts of data involving more than a million rows (see Table 5-2).

Table 5-2 Overview on the main modelling outputs of PowerACE-ResInvest

Output category	**Description**	**Identifier**	**Time horizon**	**Number of rows**
Government data	Actual RES-E Share and difference to target, prices for statistical transfers	• Year • Country	2006 – 2050	1,215
Electricity generation	Total electricity generation in pure electricity generation and CHP-plants	• Year • Technology • Country	1997 – 2050	20,412
Installed capacity	Total electricity capacity in pure electricity generation and CHP-plants	• Year • Technology • Country	1997 – 2050	20,412
Financial data	Investment for new and refurbished capacity, support paid and electricity generation costs	• Year • Technology • Country	2006 – 2050	17,010
Agent-specific data	Electricity generation of additionally installed capacity in pure electricity generation and CHP-plants, electric capacity of additionally installed plants; investment for new and refurbished capacity	• Year • Technology • Country • Agent	2006 – 2050	85,050
Balancing of potential data	Techno-economic details of each potential step including the total available potential, realised potential per agent, realised potential of all agents, refurbished potential, remaining potential	• Year • Technology • Country • Agent • Potential step	2006 – 2050	1,124,684

Source: Own illustration

The duration of one simulation run is mainly determined by the number of agents, the number of potential steps and the considered time horizon. Using a desktop computer with a 3.33 GHz processor and 3.46 GB RAM, one simulation run over 45 years takes roughly two minutes at present. This figure indicates that in its current version PowerACE-ResInvest does not have to cope with runtime problems. However, it should be considered that the model in its current version represents a deterministic model requiring only one simulation run per scenario. An amplification of the model by stochastic processes to simulate for example the electricity price development would require to increase the number of modelling runs considerably and therewith pose new challenges for optimising the calculation time. During the model development in particular algorithms used to sort the cost-potential data have turned out to be crucial for calculation time. In this context, some effort was made to reorganise the procedure and the sequence of these algorithms. In addition, the number of investment planner agents considerably influences the calculation time of the model.

5.3 Outline of the simulation model

This section provides an overview of the basic structure of the simulation model that has been developed in this thesis. In a first step, the core agents of the model, the heterogeneous investment planner agents predict the future market conditions by estimating the expected income of an investment option. The basis for this estimation is information provided by the government agent about the current and the future development of the electricity price and the available financial support. Then, the investment planner agents calculate the expected electricity generation costs based on information from cost-resource curves.

In general, low-cost potentials are exploited first, followed by the potentials with the next lowest cost. Thereby, the multi-actor structure of the model affects the structure of the cost-resource curves. This means that potential investors evaluate the profitability of one potential step differently, implying the amplification of the cost-resource curves by an additional dimension. Each investment planner agent computes the ordinary annuity for potential RET projects and launches a production request for projects with a positive annuity. As a consequence, one and the same potential step of the cost-resource is assigned to multiple values for the annuity.

Following the profitability assessment of the investment planner agents, an administrative entity decides whether a requested project obtains a permit or not. If a permit is granted, the investment planners check whether the existing plant manufacturer have sufficiently manufacturing capacity available to produce the respective renewable power plant.

At the end of each modelling period the nationally acting government agents who apply either FIT systems or a quota obligation with TGC trade revise the policy design and adapt support conditions according to the developments of RES-E generation. Furthermore, the plant manufacturer agents adapt the available manufacturing capacity according to the demand in the previous modelling period. Technological learning is calculated endogenously based on the experience curve concept to reflect potential reductions in the investment for renewable power plants. It is assumed that learning takes place on a global level and there is full knowledge spill-over between countries and companies.

The basic structure of PowerACE-ResInvest is shown in Figure 5-1.

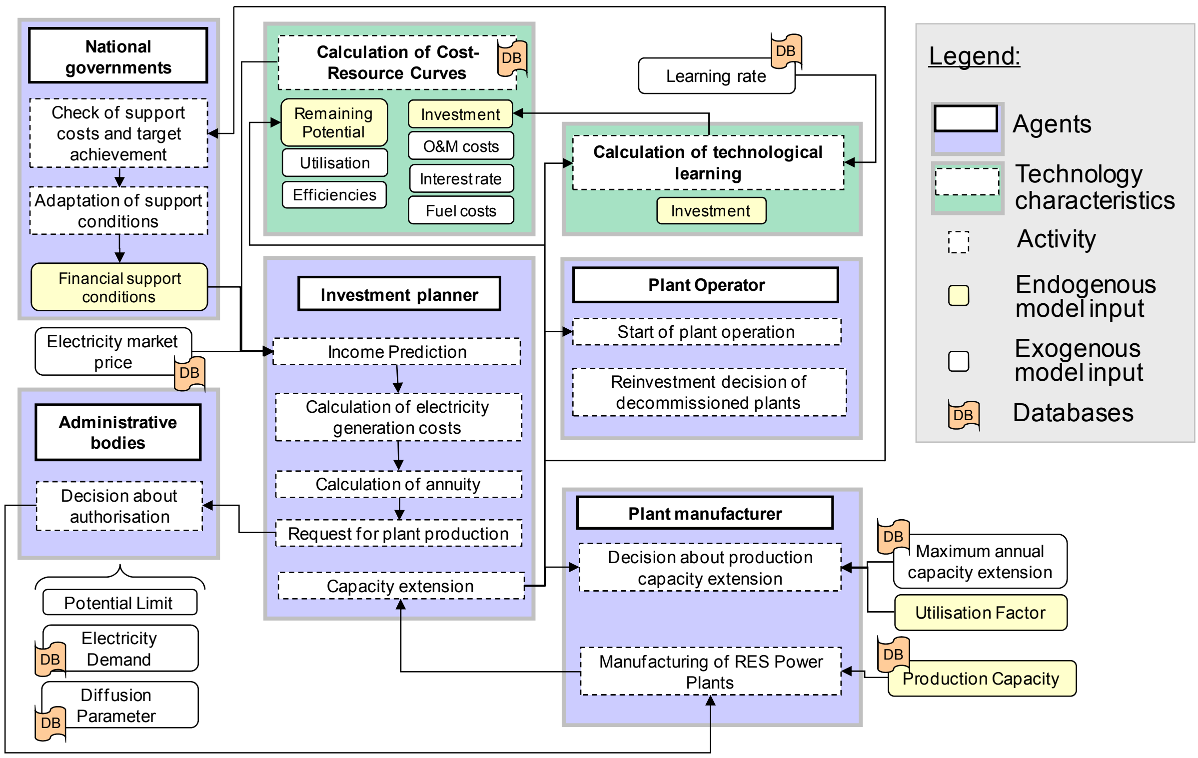

Figure 5-1 Structure of the PowerACE-ResInvest simulation model
Source: Own illustration

The model focuses on the development of RET, whilst developments in the remaining electricity sector are taken into account in a simplified manner by means of exogenous data produced with a model that covers the electricity or energy sector as a whole. Since at present RET are not exposed to full competition on the electricity market and there is a purchase obligation for renewable electricity in most European MS, it is assumed that the sale of RES-E is privileged compared to electricity produced with conventional energy conversion technologies. Taking into account probable decreases in electricity generation costs of RET and a concurrent increase in costs of technologies using fossil fuels, this situation may change in the long term up to 2050. Some RET may become competitive with other conversion technologies without requiring specific support anymore. Thus, it should be considered that the impacts of this increasing vicinity of RET to market conditions are only considered in a simplified way by using soft links. No integrated assessment of investment decisions where renewable and conventional electricity generation technologies represent alternative investment options is made in this analysis.

Subsequently, the design of the core agents in the simulation model, the investment planner agents, is described in detail.

5.4 Investment planner agents

Given the broad geographical and temporal scope of the developed model, investment planners are not depicted individually. This approach was chosen as a result of missing data availability about the agents' structural composition on the one hand and high requirements on the performance of the simulation model on the other hand. Therefore, individual investment planners are aggregated to different agent categories, whereby the specific design of the agent groups represents a challenging task. In general, individual actors could be clustered according to their lifestyles which are again characterised by attitudes and values (Bourdieu 1984). However, the concept of lifestyles rather applies to private actors and households with the intention to utilise the investment property themselves. In the context of financing RET, investment planners deciding about the construction of decentralised small-scale renewables applications such as building-integrated PV power plants or renewable heating devices could be clustered according to lifestyles. In contrast, this classification is not appropriate for commercial agents considering investments in large-scale RET including for instance offshore wind parks, which are considered besides investment in small-scale RET. Generally, large-scale investment decisions involve considerably higher investment volumes and represent commercial investment decisions. Instead of characterising investment planner agents according to their lifestyles, agents are therefore clustered according to their attitude towards adopting an innovation following the concept of Rogers (2003, p. 280ff.). The intention is to regard an increased use of RET as a process of technology diffusion (see also section 3.3). Hence, investment planner agents are classified according to their degree of innovativeness into the following agent groups[39]:

- Innovators
- Early adopters
- Early majority
- Late majority
- Laggards

Each agent group is endowed with specific characteristics as stated below.

The first issue is related to the determination of the **agents' population.** In this respect, not only information on how many agents of each agent group exist is required, but in particular information on the budget, the agents can afford and are willing to invest in renewable energy projects. However, this data is difficult to obtain. Therefore, the overall budget available for investment into renewable projects is estimated using the simulation model PowerACE-ResInvest in the following way. A simulation run is executed assuming a homogeneous agent structure. The lower limit of the selected interest rate range is chosen to obtain an upper bound for the capital availability. Since capital costs generally make up a large share of total renewable electricity generation costs and lower interest rates reduce the capital costs, the assumption of low interest rates implies rather favourable generation costs. The resulting investment

39 According to Rogers (2003, p. 280) innovativeness determines „the degree to which an individual or other unit of adoption is relatively earlier in adopting new ideas than other members of a social system .

made in each simulation year is then allocated to the investment planner agents according to the portion of each adopter category in the total number of adopters (see Table 5-3).

Second, based on the assumption that different types of economic agents have varying risk attitudes (cf. Dinica 2006, p. 465) the agent types are attributed to heterogeneous risk preferences. It is assumed that **risk perception** is **individual** and varies between the investment planner agents. This means that more risk-averse actors, represented by the late majority and the laggards, evaluate a specific project to be riskier, than a more innovation-friendly agent would do. Generally, higher risks tend to involve higher project returns or profits[40]. Therefore, profitability requirements are assumed to reflect risk attitudes in this simulation model. The internal rate of discount, which reflects the weighted average cost of capital (WACC) including costs of debt and costs of equity is used as a measure for the profitability requirement. Due to the personal risk assessment the risk-averse agents are supposed to require a higher profitability than more innovation-friendly adopters. The concrete indicator is expressed by the individual internal rates of discount used for NPV calculations (see Table 5-3).

To determine the concrete values of the discount rates, this analysis relies on typical rates that have been used in energy models focussing on the derivation of sectoral investment strategies and on market models considering actor-specific behaviour. The discount rates used in these models are typically assumed to account for market risk and are therewith higher than a typical risk-free discount rate (cf. Starrmann 2000, p. 94). In concrete terms, characteristic values of discount rates are assumed to range between 8 % and 12 %. More precisely, Hoster (1996, p. 53ff.) reports on a discount rate of 8 %, Starrmann (2000, p. 94) supposes a discount rate of 10 % and Grobbel (1999, p. 220ff.) assumes an internal rate of discount amounting to 12 %. Since no additional information on the attribution of the discount rates to the investment planner categories is available, the observed range is taken in order to determine the minimum discount rate for innovators and the maximum discount rate for laggards, which are assumed to be more risk-averse. For the intermediate investment planner categories a linear increase in the discount rate is assumed (see Table 5-3).

Third, the agent types are assumed to pursue **heterogeneous decision strategies** with regard to the kind of alternative technologies, they take into consideration for financing. When implementing this issue in the simulation model, it is assumed that more innovation-oriented agents are principally willing to invest in all RET including technologies with less practical experiences available. In contrast, it is supposed that laggards tend to invest only in technologies characterised by a certain technology and market development maturity. Therefore, the available RET options are classified according to their degree of market diffusion. It should be considered that the classification of the different technologies according to their stage of market diffusion is challenging, since there is no clear approach of how to assign the technologies to a certain diffusion stage. To mention one example, Grübler & Gritsevskii (1998) made the proposition to distinguish between existing, incremental and revolutionary energy conversion technologies.

40 This concept is based on the Capital-Asset-Pricing Model (CAPM) which describes the relationship between risks and project returns in a perfect capital market (cf. Sharpe 1964).

Hence, a coal power plant with comparatively stable investment was classified as an existing technology, a gas turbine with a certain potential for technological learning was characterised as an incremental technology, and due to a currently high investment with a considerable cost reduction potential a solar PV power plant was judged to be an example for a revolutionary technology. In line with the technological development and the market diffusion process the characterisation of a technology tends to change over time. Hence, a gas turbine can be regarded as an existing technology in the meantime.

It should be taken into account that conventional energy conversion technologies are not available for investment decisions in the model. It is rather assumed that existing agents focus on investments only in RET. Consequently, a differentiation of the available RET is realised instead of considering all conversion technologies available on the market. The share of each individual RET in the total renewable capacity is taken as an indicator for the technology maturity with regard to technological and market development to determine these technology preferences of the investment planner agents. Using this indicator, a qualitative ranking of the existing technology options is realised and each investment planner type is attributed to an individual minimum threshold for considering a certain technology option as a financing alternative. This means that some of the investment planner agents only invest in technologies, where sufficient experience in practical operation is available. This market share of RET is calculated annually and evolves dynamically over the modelling period according to the respective technology market development. The threshold for the technology preferences are outlined in Table 5-3.

Table 5-3 Classification of investment planner agents in the simulation model

Investment type	Internal rate of discount	Technology preferences	Budget availability as share of total budget
Innovators	8 %	All technologies	2.5 %
Early adopters	9 %	Technologies with a market share exceeding 0.5 %	13.5 %
Early majority	10 %	Technologies with a market share exceeding 1 %	34 %
Late majority	11 %	Technologies with a market share exceeding 5 %	34 %
Laggards	12 %	Technologies with a market share exceeding 10 %	16 %

Source: Own illustration based on the concept of Rogers (2003)

To put an example for the technology preferences in the base year 2005, laggards are assumed to consider only investments in onshore wind turbines and large-scale hydropower plants, the late majority adds biomass power plants and small-scale hydropower plants to the technology options considered for investment, whilst the early adopters extends the late majority's technology list by anaerobic digestion, geothermal power plants and biowaste power plants. Finally, innovators are the only agents who consider investment in ocean, solar power plants or offshore wind power plants in the base year. It should be noted, that the classification of technologies is realised using the exemplary indicator of the market share in total renewable electricity generation. Alternatively, the classification could be realised based on other criteria such as specific investment or according to the typical size of a power plant.

Due to the fact that investment planner agents access the same cost-resource curve, investment decisions have to be taken consecutively and a decision order has to be determined in order to avoid that one potential step is accessed by more than one investment planner at the same time. Given the character of the investment agent groups, it is assumed, that the most innovation-friendly agents are the first ones in considering a potential investment, followed by the early adopters, the early majority, the late majority and finally the laggards.

5.5 Investment planning for new power plants

The investment planning procedure for new renewable power plants represents the main element of the developed simulation model. Subsequently, the individual calculation steps realised as shown in Figure 5-1 are described in more detail.

5.5.1 Economic characteristics

In a first step, the investment planners calculate the expected electricity generation costs based on information from the cost-resource curves according to formula (5.1). Cost-resource curves provide information about the available potential to exploit RES and the involved electricity generation costs as perceived by each investment planner agent. The cost-resource curves consist of available potential steps, which are assigned to a certain level of electricity generation costs. Total costs are composed of costs for operation and maintenance, fuel costs in case of biomass technologies and the annualised investment. In case of combined heat and power generation, possible revenues of heat sales are subtracted from the costs.

$$c_{i,j,k,l} = \begin{cases} \left(\dfrac{\sum_{t=0}^{n} \dfrac{p\_f_{i,j,k}(t)}{(1+z_l)^t}}{\eta\_ele_{i,j,k}} + \dfrac{inv_{i,j,k}}{u\_ele_{i,j,k}} \right) \cdot \dfrac{(1+z_l)^n \cdot z_l}{(1+z_l)^n - 1} + \dfrac{c\_om_{i,j,k}}{u\_ele_{i,j,k}} & \text{if } i \in ELE \\ \left(\dfrac{\sum_{t=0}^{n} \dfrac{p\_f_{i,j,k}(t)}{(1+z_l)^t}}{\eta\_ele_{i,j,k}} + \dfrac{inv_{i,j,k}}{u\_ele_{i,j,k}} \right) \cdot \dfrac{(1+z_l)^n \cdot z_l}{(1+z_l)^n - 1} \\ - \sum_{t=0}^{n} \dfrac{p\_heat_k(t)}{(1+z_l)^t} \cdot \dfrac{\eta\_heat_{i,j,k} \cdot u\_heat_{i,j,k}}{\eta\_ele_{i,j,k} \cdot u\_ele_{i,j,k}} \cdot \dfrac{(1+z_l)^n \cdot z_l}{(1+z_l)^n - 1} \\ + \dfrac{c\_om_{i,j,k}}{u\_ele_{i,j,k}} & \text{if } i \in CHP \end{cases} \tag{5.1}$$

where:

$c_{i,j,k,l}$	*Electricity generation costs of plants from potential step i, technology j and country k calculated by investment planner category l [€/MWh]*
$c\_om_{i,j,k}$	*Operation and Maintenance Cost of potential step i, technology j and country k [€/MW]*
$inv_{i,j,k}$	*Investment of potential step i, technology j and country k [€/MW]*
$p\_f_{i,j,k}(t)$	*Price of fuel f for potential step i, technology j and country k [€/MWhprimary] in year t*
$p\_heat_k(t)$	*Price of heat [€/MWh] in year t*
$\eta\_ele_{i,j,k}$	*Electric efficiency of potential step i, technology j and country k[-]*
$\eta\_heat_{i,j,k}$	*Heat generation efficiency of potential step i, technology j and country k [-]*
$u\_ele_{i,j,k}$	*Annual electric utilisation of potential step i, technology j and country k [h/a]*
$u\_heat_{i,j,k}$	*Annual heat utilisation of potential step i, technology j and country k [h/a]*
z_l	*Interest rate assumed for investment planner category l [-]*
n	*Life time and amortisation period [a]*
ELE	*Set of potential steps i where the included power plants are pure electricity generation power plants*
CHP	*Set of potential steps i where the included power plants are combined heat and power generation plants*

In a second step, the investment planners predict the future market conditions by estimating the expected income of an investment option (see formula (5.2)).

$$r_{i,j,k}(t)=\begin{cases} p\_ele_k(t)+p\_cert_k(t) & if\ t\le m & \forall\ k\in Q \\ f_{j,k}(t) & if\ t\le m;\ f_{j,k}(t)\ge p\_ele_k(t) & \forall\ k\in F \\ p\_ele_k(t) & if\ t>m;\ f_{j,k}<p\_ele_k(t) & \forall\ k\in F \\ p\_ele_k(t) & if\ t>m & \forall\ k \end{cases} \tag{5.2}$$

$$r_{i,j,k,l}=\sum_{t=0}^{n_j}\frac{r_{i,j,k}(t)}{(1+z_l)^t}\cdot\frac{(1+z_l)^{n_j}*z}{(1+z_l)^{n_j}-1}$$

where:

$r_{i,j,k,l}$	*Expected income for plants from potential step i, technology j and country k calculated by investment planner category l [€/MWh]*
t	*Time step [a]*
m	*Duration of support [a]*
n_j	*Life time of technology j [a]*
z_l	*Interest rate assumed for investment planner category l [-]*
p_ele_k	*Reference electricity market price in country k [€/MWh]*
p_cert_k	*Price of the green certificate in country k [€/MWh*
$f_{j,k}$	*Fixed feed-in tariff paid for plants for technology j in country k [€/MWh]*
Q	*Set of countries where quota obligations are applied as main support scheme*
F	*Set of countries where fixed feed-in tariffs are applied as main support scheme*

Basis for this estimation is information about the expected reference electricity price development and the financial support conditions available for renewable power plants. In the simulation model, it is assumed that the financial support can be provided in terms of FIT or via quota obligations in combination with TGC. In case of FIT the overall remuneration is represented either by the tariff or the sum of the electricity price and a premium paid on top of the market price. Assuming the application of a quota obligation scheme the total income is composed of the sum of the reference electricity market price and the value of the green certificates. If the technology lifetime exceeds the duration the support is granted for, the reference electricity market price is assumed to correspond to the expected income. Whilst the electricity price and the initial FIT are fed into the model exogenously, the certificate price is calculated endogenously by the simulation model (see section 5.5.4). In the course of a simulation run, national governments may adapt the level of the FIT according to the development of RES-E generation (see section 5.7).

Then, the investment planners calculate the ordinary annuity for potential renewable energy projects, as presented in formula (5.3).

$$a_{i,j,k,l}=r_{i,j,k,l}-c_{i,j,k,l} \tag{5.3}$$

where:

$a_{i,j,k,l}$	*Ordinary annuity of plants from potential step i, technology j and country k calculated by investment planner category l [€/MWh]*
$r_{i,j,k,l}$	*Annualised expected income for plants from potential step i, technology j and country k calculated by investment planner category l [€/MWh]*
$c_{i,j,k,l}$	*Annualised electricity generation costs of plants from potential step i, technology j and country k calculated by investment planner category l [€/MWh]*

Subsequent to the calculation of the economic characteristics, which describe the available potential steps, each investment planner agent is attributed to a potential project list and sorts the projects according to the net annuity he expects. Then, the investment planners launch production requests for projects with a positive annuity in an iterative procedure. In case of a positive annuity the project profitability is at least equal to the applied interest rate. First the production request is launched for the most profitable renewable project, followed by the next potential step until any kind of limitation is achieved or no more potentials with a positive annuity are available.

5.5.2 Authorisation procedure

A project which has been judged to be a profitable investment is not necessarily built in reality. Its prospects rather depend on a procedure that provides the required building and environmental permissions. Accordingly, the market development of RET in the simulation model is assumed to be hampered due to difficulties within **authorisation entities.** These tend to issue only a certain share of the required permits. In order to take into account increasing difficulties when the installed capacity converges against the limits of the technological potential, growth is dampened stronger after having reached a determined potential limit. Thereby, the authorised production is calculated by applying an authorisation rate corresponding to the proportionate share of the production request. Permits are only granted if the national share of RES in total electricity generation of the previous year does not exceed a predefined maximum share in order to ensure that the electricity system remains manageable. In terms of concrete assumptions, a maximum limit of total renewable share in gross electricity demand is set at 90 %, whilst the share of wind electricity is additionally limited to 50 % in order to apply for the particularly volatile character of electricity generated in wind power plants. This means that restrictions resulting from the management of the electricity system are integrated in a simplified way. Formula (5.4) shows how the authorised production is calculated.

$$ap_{i,j,k,l}(t) = \begin{cases} pr_{i,j,k,l}(t) \cdot \lambda_1, \\ \text{if } q\_real_{i,j,k}(t-1) > p_{i,j,k} \cdot q\_tot_{i,j,k} \text{ and } \dfrac{\sum_{i,j} q\_real_{i,j,k}(t-1) \cdot u\_ele_{i,j,k}}{g\_tot_k(t)} < ls \\ \left(p_{i,j,k,l} \cdot q\_tot_{i,j,k} - q\_real_{i,j,k}(t-1)\right) \cdot \lambda_1 + q\_tot_{i,j,k} \cdot (1-q) \cdot \lambda_2, \\ \text{if } q\_real_{i,j,k}(t-1) \le p_{i,j,k,l} \cdot q\_tot_{i,j,k} \text{ and } \dfrac{\sum_{i,j} q\_real_{i,j,k}(t-1) \cdot u\_ele_{i,j,k}}{g\_tot_k(t)} < ls \\ 0, \quad \text{if } \dfrac{\sum_{i,j} q\_real_{i,j,k}(t-1) \cdot u\_ele_{i,j,k}}{g\_tot_k(t)} \ge ls \end{cases}$$

$$q\_real_{i,j,k}(t) + q\_add_{i,j,k}(t) = q\_tot_{i,j,k} \tag{5.4}$$

$$\lambda_2 > \lambda_1$$

where:

$ap_{i,j,k,l}$	*Authorised production potential step i, technology j, country k and investment planner category l [MW]*
$c_{i,j,k,l}$	*Annualised electricity generation cost of plants from potential step i, technology j, country k and investment planner category l [€/MWh]*
$q\_add_{i,j,k}(t)$	*Additional potential available capacity from potential step i, technology j and country k [MW]*
$q\_real_{i,j,k}(t)$	*Realised potential available capacity from potential step i, technology j and country k [MW]*
$q\_tot_{i,j,k}(t)$	*Total potential available capacity from potential step i, technology j and country k [MW]*
$p_{i,j,k}$	*Potential limit for potential step i, technology j and country k [%]*
$u\_ele_{i,j,k}$	*Annual electric utilisation of potential step i, , technology j and country k [h/a]*
$g\_tot_k(t)$	*Total electricity generation in country k [MWh]*
λ_1	*Authorisation rate if potential limit for potential step i, technology j and country k is not reached*
λ_2	*Authorisation rate if potential limit for potential step i, technology j and country k is passed*
ls	*Limit of RES-E Share [%]*

Indeed, the quantification of the share of projects that receive authorisation represents a challenging task due to the heterogeneous framework conditions on regional and on technical level. The role of administrative barriers such as receiving building permits were investigated by several studies, but results provided rather an identification of existing bottlenecks within the authorisation processes and the reasons behind than a quantification of the success rate of authorisation processes (cf. Coenraads et al. 2008b, pp. 65 - 82; Ragwitz et al. 2007, pp. 182 - 190). However, in particular the study of Coenraads et al. (2008) provides first indications about the time it takes to get a construction and operation permit, the number of authorisation bodies involved in this process. The authors indicate a rejection rate of about 30 % on average. Accordingly, 70 % of the requested projects are assumed to be authorised in the model if less than a certain share of the potential is already deployed. After having passed the potential limit, the authorisation rate is assumed to decrease to 50 %. Similar to the work realised by Sensfuss et al. (2007, p. 170), the potential limit is set to 70 %.

5.5.3 Plant manufacturing

To represent the fact that the construction of new plants is furthermore restricted by existing production facilities, the **renewable power plant manufacturer** constructs the required plants according to the available manufacturing capacity. If the demand for plants exceeds the manufacturing capacity, the manufacturer decides to extent its manufacturing capacity according to formula (5.5).

$$cap\_tot_{j,k}(t) = \begin{cases} cap\_tot_{j,k}(t-1) + \sum_i ap_{i,j,k}(t) & \text{if } \sum_{i,l} ap_{i,j,k,l}(t) \le mc_{j,k}(t) \\ cap\_tot_{j,k}(t-1) + mc_{j,k}(t) & \text{if } \sum_{i,l} ap_{i,j,k,l}(t) > mc_{j,k}(t) \end{cases}$$

$$mc_{j,k}(t+1) = \begin{cases} mc_{j,k}(t), \quad \text{if } \sum_{i,l} ap_{i,j,k,l}(t) \le pc_{j,k}(t) \\ mc_{j,k}(t) + \left(cap\_tot_{j,k}(t) - cap\_tot_{j,k}(t-1)\right), \\ \text{if } \sum_{i,l} ap_{i,j,k,l}(t) > pc_{j,k}(t) \\ \text{and } \left(cap\_tot_{j,k}(t) - cap\_tot_{j,k}(t-1)\right) < mc\_add\,max_{j,k} \\ mc_{j,k}(t) + mc\_max, \\ \text{if } \sum_{i,l} ap_{i,j,k,l}(t) > pc_{j,k}(t) \\ \text{and } \left(cap\_tot_{j,k}(t) - cap\_tot_{j,k}(t-1)\right) \ge mc\_add\,max_{j,k} \end{cases} \tag{5.5}$$

where:

$cap\_tot_{j,k}$	*Total installed capacity of technology j in country k [MW]*
$ap_{i,j,k,l}$	*Authorised production of potential step i, technology j, country k and investment planner category l [MW]*
$mc_{j,k}$	*Existing manufacturing capacity of technology j in country k [MW]*
$mc\_addmax_{j,k}$	*Maximum annual growth of manufacturing capacity of technology j in country k [MW]*

The calibration of the existing manufacturing capacity is based on developments from the past. It is assumed that the initial manufacturing capacity per technology and country corresponds to the maximum of new installations that have been realised in the previous years comprising the period from 1998 to 2005. The maximum annual growth of manufacturing capacity of one technology is supposed to correspond to the maximum increase of new installations per year observed in the past. An automatic calculation procedure using historical renewable capacity data has been implemented into the model allowing for the adaptation of the parameters if new statistical data is available.

5.5.4 Tradable green certificate prices

As described in section 2.1.4, the quota obligation system in combination with TGC represents a quantity-driven support scheme. This means that the certificate price is principally established based on the generation costs of the marginal renewable generation unit needed to meet a quota target. However, the formation of certificate prices in reality does not necessarily reflect marginal generation due to market imperfections including strategic behaviour of market participants. Similarly, potential investors may require risk premiums in order to compensate the uncertain future development of the TGC prices (Dinica 2006).

To get an indication about the TGC price, a price forecast for the green certificates is calculated on an annual basis as shown in Figure 5-2. Therefore, the marginal renewable generation unit is determined on country level in the following way. Electricity generation costs are calculated for each potential step as described in section 5.5.1 and sorted according to the electricity generation costs in ascending order. Then, a hypothetical investment planning procedure is realised as described in section 5.5. Each potential project passes through the investment planning procedure including the authorisation procedure and the consideration of manufacturing capacities in an iterative way. At the end of each iteration step, the computed expected share of renewables in electricity generation is compared to the internal quota target for the respective year. As soon as the quota target is achieved, the iteration finishes and the electricity generation costs of the last unit required are taken as an indicator for the calculation of the TGC price. The TGC price is finally calculated on a national basis by subtracting the reference electricity price from the generation costs. One difficulty regarding the price formation of the TGC in a multi-agent model, where agents evaluate the projects' profitability heterogeneously represents the selection of the corresponding discount rate. Electricity generation costs are calculated using a unique interest rate of 10 % corresponding to the mean value of the applied interest rates ranging from 8 % to 12 %.

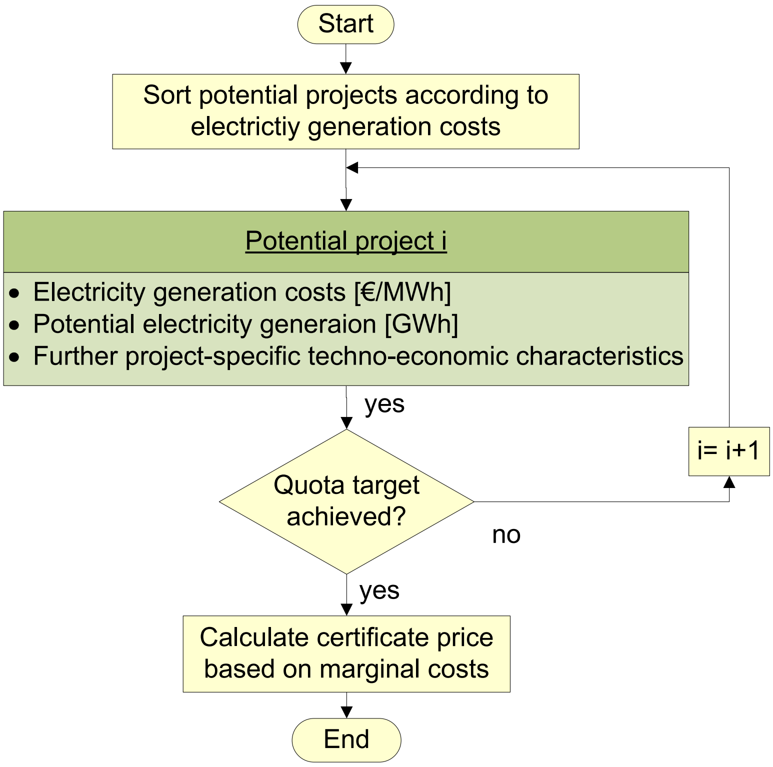

Figure 5-2 Flow chart of tradable green certificate price formation process
Source: Own illustration

The implemented price formation procedure does not necessarily lead to a precise achievement of the quota targets. Given that the investment planner agents evaluate the profitability of projects differently, the quota price calculated based on a uniform interest rate provides a price indication which may imply, that the quota target is either not achieved or exceeded. In addition, the price indication is calculated on an annual basis, meaning that the price cannot be adapted with a changing degree of target fulfilment. The implemented price formation process is able to reflect real-world conditions, such as the existence of heterogeneously acting investors or strategic behaviour of actors. These aspects may considerably affect the resulting prices.

5.5.5 Balancing of multi-actor cost-resource curves

Given the existing constraints upon the renewable energy potential, cost-resource data has to be balanced after the realisation of an investment in a renewable energy project, as the remaining potential available for other investments decreases. In particular, investment decisions taken by multiple heterogeneous agents require additional technical efforts compared to a situation where only one centralised investment planner exists. The reason for this is that each investment planner agent evaluates the profitability of renewables projects in a different way and does not necessarily consider investments in all existing renewable potential steps. As a consequence, one potential step is no longer characterised unambiguously by the same economic indicators, but rather by a set of economic indicators, each pertaining to one agent. By adding this additional dimension to the cost-resource curve, a new type of dynamic cost-resource curve considering multi-agent situations as shown in Figure 5-3 evolves.

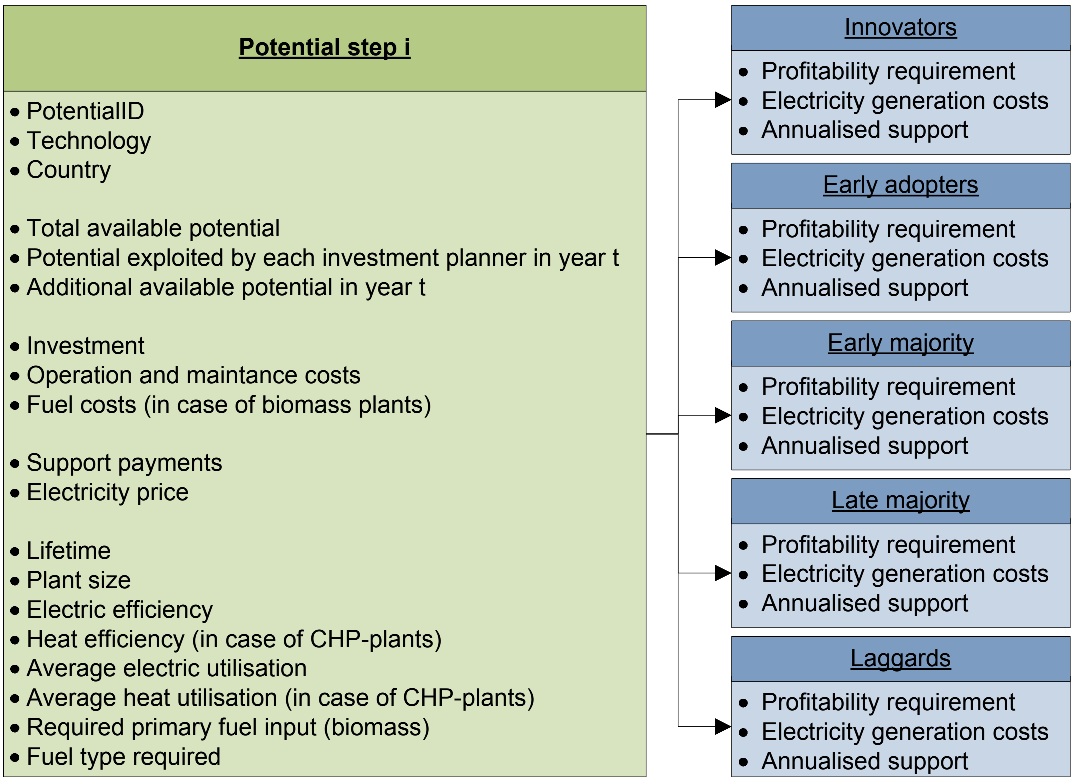

Figure 5-3 Composition of one potential step characterised by multiple economic indicators
Source: Own illustration

To balance the amplified multi-agent cost-resource curves in the simulation model PowerACE-ResInvest, the techno-economic information about both existing and unexploited renewable energy projects is bundled in one object of the type *RESPotentialOverview*. This information includes the total potential available, the remaining additional potential and the exploited potential. In case of the exploited potential this information is combined with the corresponding investment planner agent responsible for the construction of the project. Furthermore, economic indicators are calculated based on the individual requirements of each investment planner category using the information stored within the object *RESPotentialOverview*. Before the start of one simulation period, each investment planner agent is assigned an extract from the object *RESPotentialOverview* reflecting all technology options the investment planner considers as an investment alternative and the respective profitability requirements. After the realisation of an investment into a renewable energy project the remaining potential and the constructed potential is updated in the overview object *RESPotentialOverview* as well as in the extracted technology option lists of the other investment planner categories.

Figure 5-4 schematically represents the balancing procedure of cost-resource curves capable to reflect multi-agent investment decisions.

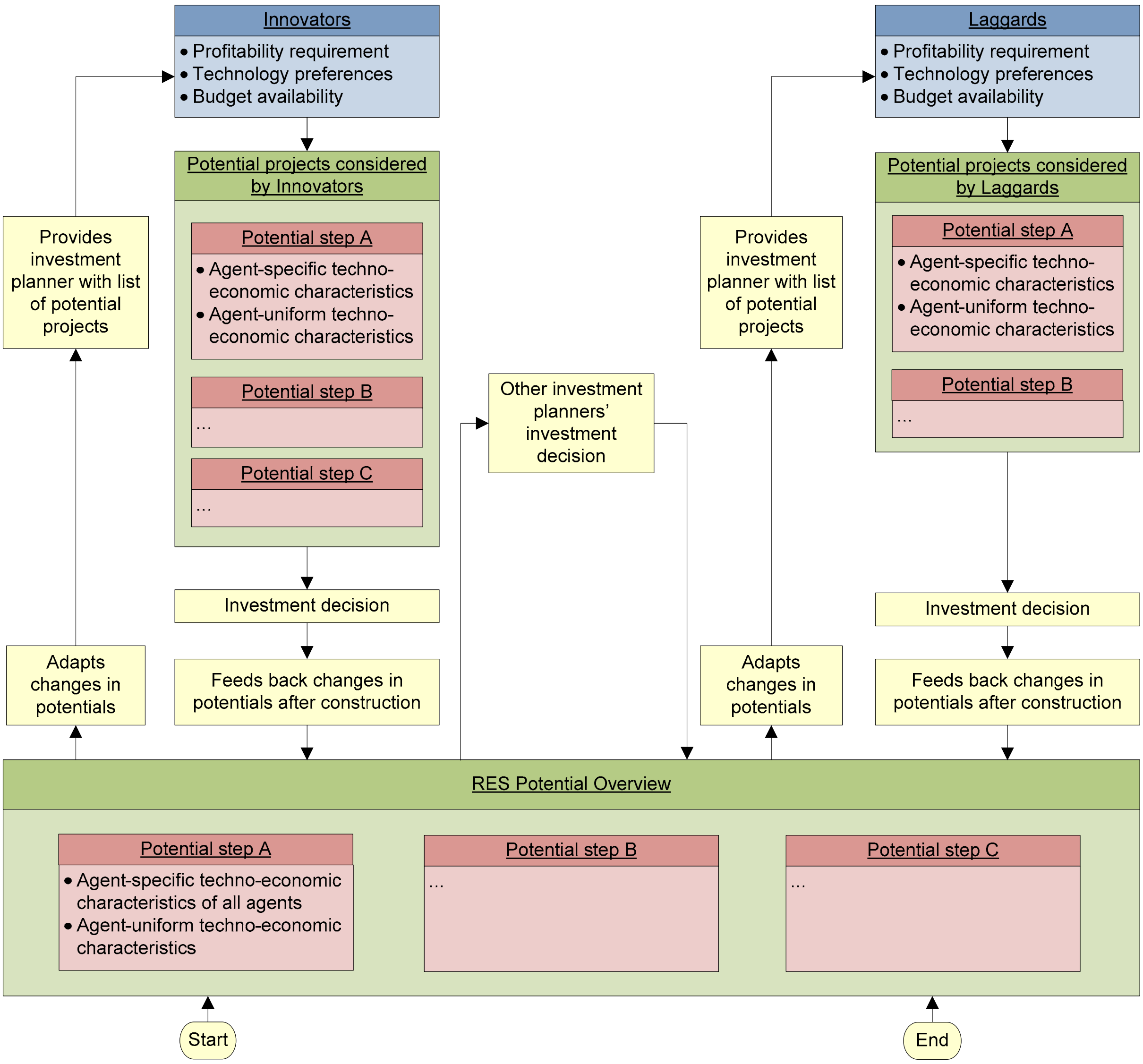

Figure 5-4 Overview of balancing procedure with regard to multi-actor cost-resource curves and corresponding economic characteristics. The process is represented exemplarily for two investment planner agents and three potential steps

Source: Own illustration

Subsequent to the balancing of the renewable energy potentials, investment is adapted in order to apply for technological learning.

5.6 Reinvestment into existing plants

Besides the decision about investments in additional renewable electricity generation capacity, the potential replacement of plants that have reached the end of their technical lifetime has to be taken into account. This is due to the fact that the modelling horizon exceeds the technical lifetime of most renewable power plants. As soon as a renewable power plant achieves the end of its technical lifetime, investors have to decide in favour or against the substitution of the existing plant. In general, one can assume that this reinvestment is realised based on profitability considerations similar to the case of investments in new renewable capacity. The decision on the reinvestment involves some peculiarities, which do not have to be considered when investing in new renewable energy capacity. This includes the fact that three different types of renewable power plants in operation are depicted in PowerACE-ResInvest. These three plant categories can be distinguished according to the degree of information available about these plants (see Table 5-1).

Tabelle 5-1 Simplified structure of the three renewable power plant (RPP) categories according to the degree of information available

New RPP in operation - A -	Historic RPP in operation - B -	Historic RPP in operation - C -
• Capacity installed • Year of commissioning • Year of phaseout • ID of investor affiliated • Project-specific techno-economic characteristics	• Capacity installed • Year of commissioning • Year of phaseout • - • -	• Capacity installed • - • - • - • -

Source: Own illustration

The first group comprises all the renewable power plants that have been built during the modelling horizon, whereas the second and the third category include an aggregation of all renewable power plants that have already been operating in the start year of the simulation. In case of the first category, all the techno-economic parameters of the plants in operation are well known, whilst only limited data on the plant characteristics is available for the plants in operation that are based on historical statistics. More precisely, the statistical data does not provide data on project-level but aggregated to a country and technology level. Looking for example at wind energy plants, no information about the location-specific wind conditions is available. Therewith, the crucial parameter for calculating the profitability of the individual projects is missing in case of plant category B and C. The latter plant categories are distinguished, according to whether the year of initial operation is known or not. Category B is composed of plants, where the year of the initial operation is known. In contrast, plants of the third category comprises all plants installed before the base year, the first year of the historical renewable capacity data fed into the model, where the year of the installation is not even known.

Thus, the investment decision for the first category of renewable power plants is realised similar to investments in new plants based on profitability criteria calculated by the investors. In contrast, the reinvestment in plants of the category B or C is assumed to take place automatically without an explicit decision process. As project-specific techno-economic characteristics including investment, variable costs, utilisation and efficiencies are not known for the plant types B and C, these parameters are approximated. For this purpose, average parameters of all power plants in operation that pertain to a certain technology category are calculated and assumed to represent the techno-economic characteristics, as shown in formula (5.6). For instance the respective investment is estimated to add up to the average investment of operating plants, corrected by annual learning effects (see formula (5.6)).

$$param\_avg_{j,k} = \sum_{i \in PiO} param_{i,j,k} \cdot \frac{1}{m}$$
$$c\_inv\_avg_{j,k}(t) = \sum_{i \in PiO} c\_inv_{i,j,k}(t-1) \cdot \frac{1}{m} \cdot idf \qquad (5.6)$$

where:

$param\_avg_{j,k}$	*Average parameter of power plants in operation from technology technology j and country k [€/MW]*
$param_{i,j,k}$	*RPP-specific parameter for step i, technology j and country k [€/MW]*
$c\_inv\_avg_{j,k}(t)$	*Average investment of power plants in operation from technology j and country k in year t [€/MW]*
$c\_inv_{i,j,k}(t-1)$	*Investment of plants from potential step i, technology j and country k in year t-1 [€/MW]*
t	*Time step [a]*
m	*Number of power plants in operation [-]*
idf	*Investment degression factor [-]*
PiO	*Set of power plants in operation*

Whilst in case of category B, the installation year of the plant and the year of the reinvestment are known, additional assumptions have to be made for plants of category C. As no information about the installation year is available, it is supposed that the renewable capacity installed before the historic base year is substituted in equal shares during the whole period of the simulation horizon according to formula (5.7).

$$cap\_reinv_{j,k}(t) = \begin{cases} \sum_i cap\_plant\_op_{i,j,k,l,m} & if\ a_{i,j,k}(t) > 0;\ m + n_j = t \quad \forall l \in A \\ cap\_tot_{l,m} - cap\_tot_{l,m-1} & if\ m + n_j = t;\ m < by \quad \forall l \in B \\ cap\_tot_{l,by} \cdot \frac{1}{n_j} & \forall l \in C \end{cases} \qquad (5.7)$$

where:

cap_reinv	*Capacity reinvested in technology j and country k*
$cap\_plant\_op_{i,j,k,l,m}$	*Capacity of plant in operation for potential step i, technology j, country k, plant type l and commissioned in year m*
$a_{i,j,k}$	*Annuity of reinvestment of plant in operation*
n_j	*Lifetime of technology j*
$cap\_tot_{l,m}$	*Total capacity of plant type l installed in year m*
t	*Time step [a]*
l	*Type of renewable power plant in operation*
by	*Base year*
A	*Set of renewable power plant in operation type A*
B	*Set of renewable power plant in operation type B*
C	*Set of renewable power plant in operation type C*

5.7 Policy maker

As outlined in section 3.1, the high relevance of policy design for the future development of RES requires an adequate representation of the political framework conditions in the simulation model. In order to be able to analyse current policy developments in the field of renewable energies, the design of the policy maker agents integrated into the model are intended to reflect recent developments in the European renewable policy landscape.

In principle, two types of policy makers crucial for the renewable energy sector can be distinguished. The **European institutions** including the European Commission, the European Parliament and the European Council determine future targets for the RES development and the legal framework conditions on European level. The second type corresponds to **national governments**, who are responsible for translating the targets set on European level into concrete support measures. National governments are represented as one crucial group of agents in the simulation model, whilst the European institutions are not represented in terms of independent agents. A central role in the simulation model is attributed to national governments, as these are directly responsible for the individual arrangement and design of the support scheme shaping the direct financial framework conditions for investments into renewable energy projects.

The government agent is assumed to apply either FIT systems or a quota obligation with TGC trade. The government agent who implements a FIT system determines the support level available for each RET via the FIT and the quantity of newly installed renewable capacity evolves as a consequence of the price. In contrast, the government agent using a quota obligation as support instrument first establishes a target for the use of RET, and the certificate price is formed as a result of the quantity determined by the government. In addition, the government agents estimate the policy costs arising from an increased use of RET. In this thesis, the policy costs are understood as the total amount paid for one unit of renewable electricity – corresponding either to a fixed FIT or the sum of the reference electricity price and the TGC price – minus the market value of the renewable electricity. The value of renewable electricity is thereby assumed to equal the reference electricity price[41].

Government agents represented in the simulation model intend to fulfil targets set on EU level on the one hand and to keep costs for the support of renewables on a level acceptable for the citizens on the other hand. Given existing uncertainties regarding the investors' behaviour, technological progress and other influencing factors, support policies should be revised from time to time. Thus, potential reactions of the government agents are analysed in this thesis. In fact, governments dispose of various options of adapting existing policy measures with regard to steering the future RES development in a particular direction. Only to mention some examples, exceeding policy costs can be addressed by reducing the support level for all or only for one technology or by setting a cap for the amount of electricity supported either on

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41 Additional aspects may affect indirectly the market value of electricity (cf. Sensfuss et al. 2008). However, these aspects are neglected for the calculation of the policy costs.

technological level or for all RET. In case of problems with regard to target achievement, tariffs can be increased or price-driven support measures can be substituted by quantity-driven support measures[42].

As it is difficult to predict in which way governments react towards certain developments and to determine the degree of change, an example of how potential reactions could look like is implemented exemplarily for the government agent who applies a FIT system. The detailed implementation details are described in section 5.7.1. In particular, the implications of certain behaviour on policy costs will be analysed in the context of the scenario calculations.

Finally, the government agents deal with the recently introduced flexibility measures by calculating price indications for statistical transfer of renewable electricity as described in section 5.7.2.

Summarising, the main purposes of the government agent in the simulation model can be characterised as follows:

- to provide financial support as described in section 5.5;
- to adapt the financial support conditions dynamically depending on target achievement in case of governments using FIT-systems;
- and to calculate price indications for statistical transfer.

5.7.1 Dynamic behaviour towards the degree of target achievement

Governments using FIT systems are assumed to react towards the degree of target achievement. This means that they increase tariffs if the RES-E target is not met and decrease tariffs if the achieved share of RES-E generation exceeds the target. In the first case, tariffs are assumed to increase by 5 % annually, whilst the determination of the reduced tariff is determined as follows.

It is supposed that the governments know the costs of the most expensive project in each technology category that has been built during the preceding time period. In order to avoid the discouragement of potential investors as a result of too abrupt changes in the financial support conditions, the tariff adaptation mechanism is based on a gradual approach. Thus, the government sets the new tariff to the mean value of the original tariff level and the electricity generation costs of the most expensive project built during this time step according to formula (5.8). Tariffs are only increased if the difference to the target exceeds a threshold of 5 %.

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42 Thereby, it should be noted, that quantity-driven support measures do not automatically guarantee target achievement in practice.

$$f\_new_{j,k}(t+1)=\begin{cases} f_{j,k}(t)*1.05 & if\ diff\_target(t)<-0.05 \quad \forall k\in F \\ f_{j,k}(t) & if\ -0.05\le diff\_target(t)\le 0 \quad \forall k\in F \\ \frac{f_{j,k}(t)+c\_marg_{j,k}(t)}{2} & if\ diff\_target(t)>0 \quad \forall k\in F \end{cases} \tag{5.8}$$

where:

$c\_marg_{j,k}$	*Electricity generation costs of the marginal renewable power plant from technology j and country k [€/MWh]*
$f_{j,k}$	*Fixed feed-in tariff paid for plants for technology j in country k [€/MWh]*
$f\_new_{j,k}$	*Adapted fixed feed-in tariff paid for plants for technology j in country k [€/MWh]*
$diff\_target_k(t)$	*RES-E share target in country k - Actual RES-E share in country k*
F	*Set of countries where fixed feed-in tariffs are applied as main support scheme*
t	*Time step [a]*

5.7.2 Flexibility measures in terms of statistical transfers

Since the target setting procedure of Directive 2009/28/EC did not take into account the heterogeneous resource availability of RES, a pure national target fulfilment does not necessarily involve the most cost-effective deployment of RES on EU-level. The EC facilitates governments to compensate missing renewable final energy with the support of other MS or third (non-EU) countries to enhance a preferably cost-effective deployment of RES. These compensatory mechanisms enabled by the European legislation are referred to as **flexibility measures**. In order not to disrupt existing successful support schemes at national level, the use of flexibility measures remains restricted, as MS may decide whether they make use of the flexibility mechanisms or not.

Flexibility measures may take either the form of **statistical transfers**, **joint projects** or **joint support schemes**. Their detailed design including questions regarding balancing of costs and benefits has not been defined yet. The three types of flexibility mechanisms can be distinguished according to different features. Whilst joint projects and joint support schemes are in principle supposed to be realised in terms of **bilateral agreements**, statistical transfers can be exchanged either via bilateral negotiations or via an **international trading mechanism**. This raises the question, which prices will emerge from such kind of international cooperation mechanisms. Whilst it seems to be difficult to estimate prices established in bilateral agreements, the developed simulation model may help to investigate possible price formation procedures under an international trading mechanisms.

The price determination requires a detailed knowledge on energy conversion costs of the deployed and additionally available renewable potentials. This knowledge is provided by the simulation model developed in this thesis. Consequently, potential price determination procedures for statistical transfers assuming an international price formation procedure are investigated based on the simulation model PowerACE-ResInvest. Subsequently, the concept of statistical transfers is described in more detail.

Statistical transfer means that renewable final energy provided by a country with a renewable share exceeding the domestic target may be accounted for target achievement of another country, being short of renewable final energy. Subsequently, countries with a potential surplus of renewable final energy will be referred to as **'exporting countries'**, whilst countries with problems regarding target achievement are referred to as **'importing countries'**. The statistical transfer of renewable final energy does not require its physical exchange. In principle, only energy provided in addition to the domestic target can be exported. Figure 5-5 provides a schematic overview of the principle of statistical transfers.

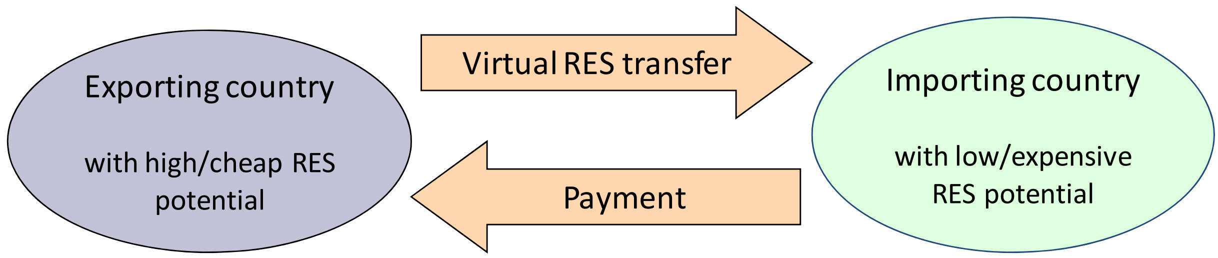

Figure 5-5 Schematic illustration of the basic principle of statistical transfer
Source: Own illustration

Although renewable final energy may be statistically transferred in terms of electricity, heat or biofuels, this thesis focuses on the analysis of statistical transfers in the electricity sector. Potential feedbacks of statistical transfer on TGC prices or on the dynamic tariff setting for FIT are not considered.

Depending on the quantity of surplus electricity available on the market, the price determination procedure may be realised considering different perspectives including the price expectations of exporting countries as well as prices resulting from the willingness-to-pay of potential importing countries. If the demand for renewable electricity exceeds supply, a price determined by exporting countries is likely to evolve. In contrast, a price indication may originate from the consumers' willingness to pay, if supply exceeds demand. However, it would be also conceivable that suppliers intend to sell the surplus electricity at any price in a scenario, where demand exceeds supply, if the surplus electricity is considered as sunk costs.

Accordingly, two examples for an international trading mechanism taking into account both the perspective of exporting and of importing countries are investigated. In addition, price calculations may be based either on **marginal generation costs** on the one hand or on **average generation costs** on the other hand. For the determination of the final value of the renewable electricity available for statistical transfer reference electricity prices are subtracted.

Given the complex circumstances of the price building procedure, both mechanisms presented can only be taken as an indication for a potential price range. In both cases, it is assumed that trade is only permitted in countries that have fulfilled their domestic target. The concrete implementation of both investigated price determination mechanisms is described subsequently.

5.7.2.1 Price determination mechanism for statistical transfers in a seller's market

In a seller's market or in a market where surplus renewable electricity is available, the price of the transferred renewable electricity is supposed to result from the cost characteristics of the surplus electricity available. In this situation, it is assumed that exporting countries intend to get a reimbursement for the additional costs that have to be borne by their own citizens in addition to the costs of reaching the domestic target. Therefore, prices are calculated based on average generation costs. This helps increase acceptance of society for surplus RES-E generation.

Marginal pricing is not investigated due to the following reason. Since the model design is able to exploit also rather cost-intensive technology options such as PV, the resulting price signal could in principle achieve extremely high levels, so that importing countries would probably not be willing to pay the resulting costs for the statistical transfer of RES-E in the absence of any national benefit.

To calculate the final value of the electricity available for statistical transfers, diverging reference electricity prices in European MS have to be considered. Since it is assumed that no physical exchange of electricity is performed, the surplus electricity generated is consumed in the exporting country. Therefore the reference electricity price of the exporting country is subtracted from the potential-step specific electricity generation costs of the surplus electricity produced. The difference between electricity generation costs and reference electricity price will be referred to as the transfer price. Then, a merit order curve of the potential-step specific transfer prices of surplus electricity is established on country level in all potential exporting countries until the surplus electricity generation is exploited. Finally, the average price of the transfer price merit order is calculated on a national basis (see Figure 5-6).

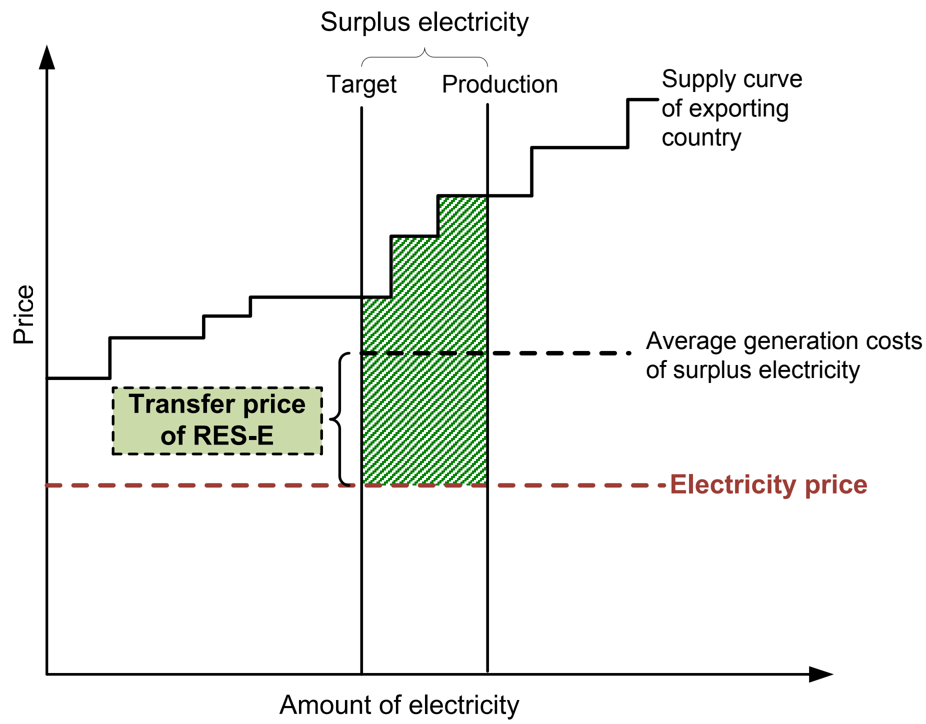

Figure 5-6 Schematic illustration of price determination mechanism in a seller's market
Source: Own illustration

5.7.2.2 Price determination mechanism for statistical transfers in a buyer's market

The second price determination procedure takes into account the price expectations from potential importing countries. Reflecting the determination of the transfer price based on the principle of willingness-to-pay of potential importing countries, it is assumed that in general consumers would prefer to produce renewable electricity domestically to take advantage of the associated potential benefits of RES-deployment. Hence, potential importers are assumed to realise statistical imports of renewable electricity only, if the transfer price of the imported electricity is lower than the domestically available RES-E generation options.

The first step of the price determination mechanism is to establish a merit order of the unexploited potential steps for all potential importing countries until the national interim target is achieved (see Figure 5-7). One additional issue has to be considered to determine a price indication. If the demand for surplus electricity exceeds the supply, potential importing countries compete among each other for the electricity available for statistical exports. Thus, the question arises which countries receive the statistical exports at what price. To figure this out, all the national merit order curves are merged in reversed order as shown in Figure 5-7 to an international merit order curve.

It is assumed that the demand for statistical imports of RES-E specified in the potential step corresponding to the highest transfer price in the international merit order curve is satisfied first, followed by the next potential step until the demand for statistical RES-E imports is exploited. This accounts for the fact that countries facing comparatively high costs of domestic target fulfilment are served first, as they are willing to pay higher transfer prices. The transfer price of the last potential step finally sets the price of the transfer electricity. Assuming that importing countries know this price, importing countries apparently are not willing to pay a higher price than necessary to statistically import renewable electricity. In contrast to the price determination mechanism based on surplus supply of renewable electricity, this determination procedure is based on the concept of marginal pricing.

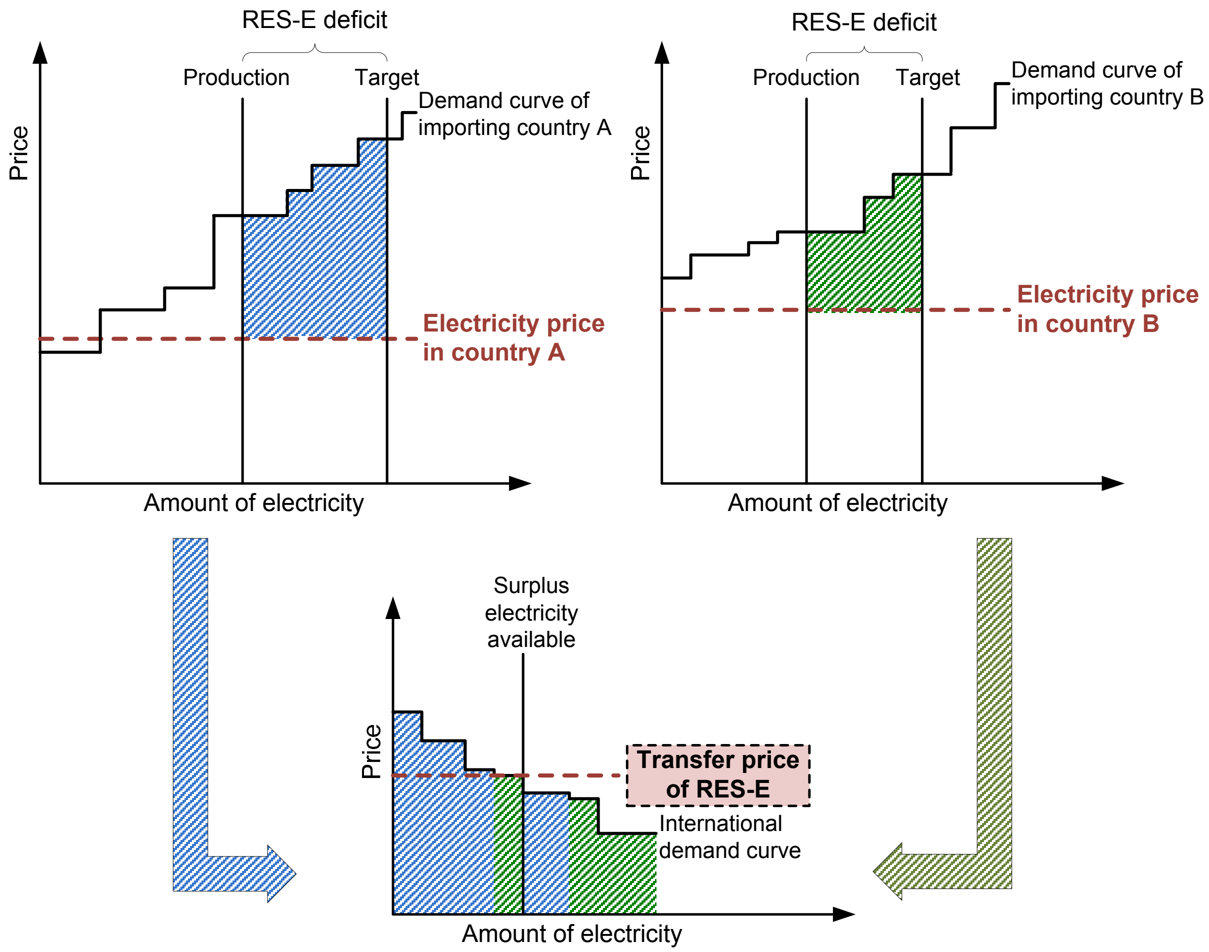

Figure 5-7 Schematic illustration of price determination mechanism in a buyer's market.
Source: Own illustration

5.8 Technological learning

In order to reflect potential changes in the production costs of RES-E, **technological learning** is calculated endogenously based on the experience curve concept. It is assumed that learning takes place on global level, supposing there are global knowledge spill-over between countries and companies. The global installed capacity is therefore used to represent the accumulated experience level of a technology. As PowerACE-ResInvest does not cover non-EU countries, the non-EU development of RES-E is fed into the model exogenously. The future installed capacity data for RES-E technologies in the non-EU world up to 2030 is estimated based on the IEA 2004 'Alternative Scenario' of their *World Energy Outlook 2004* (International Energy Agency [IEA] 2004). Since the World Energy Outlook covers the time horizon up to 2030 annual growth rates between 2021 and 2030 are extrapolated in order to approximate the installed capacity from 2031 to 2050[43].

Table 5-4 Capacity development of RES-E technologies in non-EU countries to 2050

	Installed Capacity [GW]						Annual Growth Rates [% per year]			
	2001	2010	2020	2030	2040	2050	2001-10	2011-20	2021-30	2031-50*
Biomass	22	35	60	102	174	296	5.3	5.3	5.5	5.5
Geothermal	8	12	17	25	38	58	4.8	3.2	4.2	4.2
Hydro	604	744	880	1,014	1,169	1,347	2.3	1.7	1.4	1.4
Solar PV	1	9	29	90	278	860	24.8	13.0	12.0	12.0
Solar thermal	0	1	3	10	38	149	9.4	9.4	14.5	14.5
Tidal/Wave	0	0	0	1	8	61	0.0	2.3	45.2	22.6
Wind onshore	7	31	83	214	551	1,417	18.4	10.4	9.9	9.9
Wind offshore	0	1	5	19	73	274	40.1	24.1	14.1	14.1
Total RES-E	**643**	**833**	**1,077**	**1,476**	**2,329**	**4,463**	**2.9**	**2.6**	**3.2**	**5.7**

Source: Own calculations based on International Energy Agency [IEA] (2004), Alternative Scenario

The investment for each potential step is then calculated and adapted on an annual basis according to formula (5.9).

$$c\_inv_{i,j,k}(t) = c\_inv_{i,j,k}(t-1) \cdot \left(\frac{\sum_k cap\_tot_{j,k}(t) + cap\_nonEU_k(t)}{\sum_k cap\_tot_{j,k}(t-1) + cap\_nonEU_k(t-1)} \right)^{-E_j} \qquad (5.9)$$

$$E_j = -log_2(1 - LR_j)$$

where:

$c\_inv_{i,j,k}$	*Investment of potential step i, technology j and country k [€/MW]*
$cap\_tot_{j,k}$	*Total installed capacity of technology j in country k [MW]*
cap_nonEU_j	*Total installed capacity of technology j in non-EU countries [MW]*
E_j	*Experience parameter of technology j [-]*
LR_j	*Learning rate of technology j [-]*

43 In case of tidal and wave capacity data half of the annual growth rate of 2021-2030 since growth rates in this time horizon were considered to be comparatively high.

5.9 Climate change impacts on hydropower generation

As described in section 2.3, climate change affects the use of RES in the electricity sector to a certain extent. Therefore, the impact of climate change is considered for the model-based representation of the future development of RES-E in Europe. However, the quantification of climate change impacts on RES-E generation involves a high degree of uncertainty. As shown in section 2.3, quantitative data of climate change impacts on RES that covers Europe as a whole is not available for all RES. In this context, it is decided to analyse the impact of climate change on hydropower generation due to data availability and the high vulnerability of hydropower to climate change (see section 2.3).

Information about changing hydropower potential available in the literature is used for this analysis. Thus, a study that estimated the impact of climate change on hydropower potential for Europe on a national scale was resorted to Lehner et al. (2005). The authors calculated the influence of climate change on the gross hydropower potential as well as its impact on the already developed hydropower capacity. In the study mentioned, percentage discharge changes with respect to historical weather conditions including average values between 1961 and 1990 were calculated, using the integrated global water model WaterGAP. The underlying assumptions of the study regarding climate change input data assume an average annual increase in CO_2 emissions by 1 % leading to a CO_2 concentration of 600 ppm by 2070. It is supposed that this change in CO_2 emission concentration involves an increase of average temperature by 2.3 °C by 2070. The authors of the study assess the change in the developed hydropower potential using climate data inputs from the General Circulation Model (GCM) HadCM3 and ECHAM4. Occurring deviations resulting from the use of different GCM indicates a certain degree of uncertainty regarding the quality of results. Nevertheless, a first indication of the impact of climate change on hydropower utilisation is be provided.

In order to integrate the results into the PowerACE-ResInvest model, the given changes in hydropower potential originating from data of the HadCM3 model are transferred into percentage changes of utilisation (see Figure 5-8). Assuming that changes occur on a straight-line basis over time, the given changes are broken down for each time increment of one year. Potential influences of a modified utilisation on energy conversion efficiencies are neglected. Finally, the annual climate correction factor is determined by transforming the percentage changes against the base year 2005 into percentage changes against the previous simulation year. Figure 5-8 shows that climate change affects the hydropower potential in each country differently.

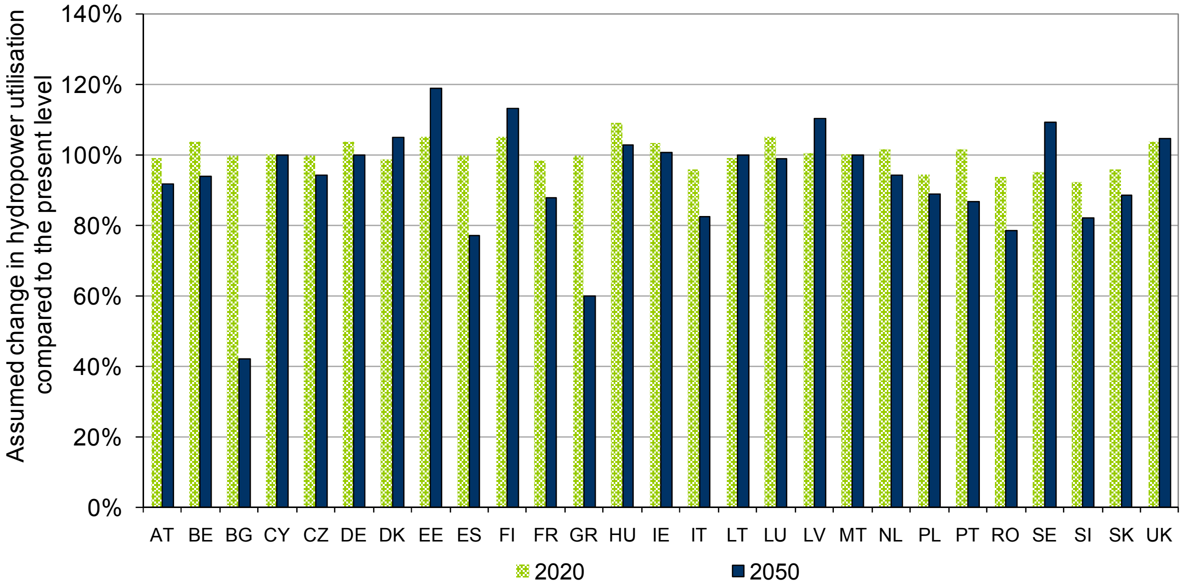

Figure 5-8 Assumed change in hydropower utilisation compared to the base year 2005

Source: Own illustration with data based on Lehner et al. (2005)[44]

According to Lehner et al. (2005) the hydropower utilisation of existing hydropower plants tends to increase in Northern European countries such as Estonia, Finland, Latvia and Sweden, whilst hydropower utilisation in Southern European countries including Bulgaria, Greece and Spain is expected to decrease considerably. According to the approximations realised in this analysis the hydropower potential increases by 19 % until 2050 in Estonia, whereas hydropower potential in Bulgaria in 2050 accounts for only 42 % of the present potential.

The modified annual utilisation and the corresponding changes in the electricity output is calculated according to formula (5.10).

$$u\_ele\_clim_{i,j,k}(t) = u\_ele\_{i,j,k}(t-1)\cdot ccf(t) \qquad \forall\, j \in HYD$$
$$gen\_tot_{j,k}(t) = \begin{cases} cap\_add_{j,k}\cdot u\_ele\_clim_{i,j,k}(t) + gen\_tot_{j,k}(t-1)\cdot ccf(t) & \forall\, j \in HYD \\ cap\_add_{j,k}\cdot u\_ele_{i,j,k}(t) + gen\_tot_{j,k}(t-1) & \forall\, j \notin HYD \end{cases} \qquad (5.10)$$

where:

$u\_ele\_clim_{i,j,k}$	*Climate change corrected annual electric utilisation of potential step i, technology j and country k [h/a]*
$u\_ele\_{i,j,k}$	*Annual electric utilisation of potential step i, technology j and country k [h/a]*
ccf	*Annual climate correction factor [-]*
$gen\_tot_{j,k}$	*Total electricity generation of technology j in country k [MWh]*
$cap\_add_{j,k}$	*Additional electric capacity of technology j in country k [MW]*
HYD	*Set of hydropower technologies (small-scale and large-scale hydropower)*

44 Lehner et al. (2005) provide changes in the developed hydropower potential by 2020 and 2070. Figures shown for 2050 are estimated based on linear interpolation.

Since only a limited growth of hydropower capacity is expected in European countries, calculations are based on the impact on the hydropower capacity already developed. Looking at the influence of climate change on hydropower generation, one should consider that results are estimated based on various assumptions, including uncertainties regarding for instance the input from the GCM models.

5.10 Interactions with the electricity system

Due to existing interdependencies of renewable electricity generation and the remaining part of the power system, the development of RES-E technologies is not regarded separately from the development of the electricity system. This includes the development of the electricity demand on the one hand and the structure of electricity supply including the mix of conventional conversion technologies on the other hand. PowerACE-ResInvest is used as part of a hybrid modelling system (HMS) where the subsectors of the energy system are modelled by different bottom-up models to consider these systemic aspects of existing interrelations within the electricity system,. This HMS has originally been developed as part of the ADAM project, a research project funded within the 6th framework programme of the European Commission[45]. Project partners investigated final energy demand by means of sectoral demand models focussing each on the residential, service, industry and transport sector (Jochem et al. 2007). Then, Paul Scherrer Institute (PSI), Switzerland applied the optimising energy model EuroMM combining final energy demands, the renewable electricity generation sector and the conventional energy conversion. All bottom-up models have been connected using soft-links, where required. Models have partly been run in an iterative procedure to take into account potential interrelations between the sectors. Additional information including a first indication on CO_2 pathways, electricity prices and CO_2 prices was provided by the energy sector model POLES. Figure 5-9 provides an overview of the modelling system applied in the ADAM project.

45 The modelling work was carried out in the context of Work Package M1, dealing with mitigation of climate change in the European energy sector. Additional information about the project can be found at http://www.adamproject.eu/.

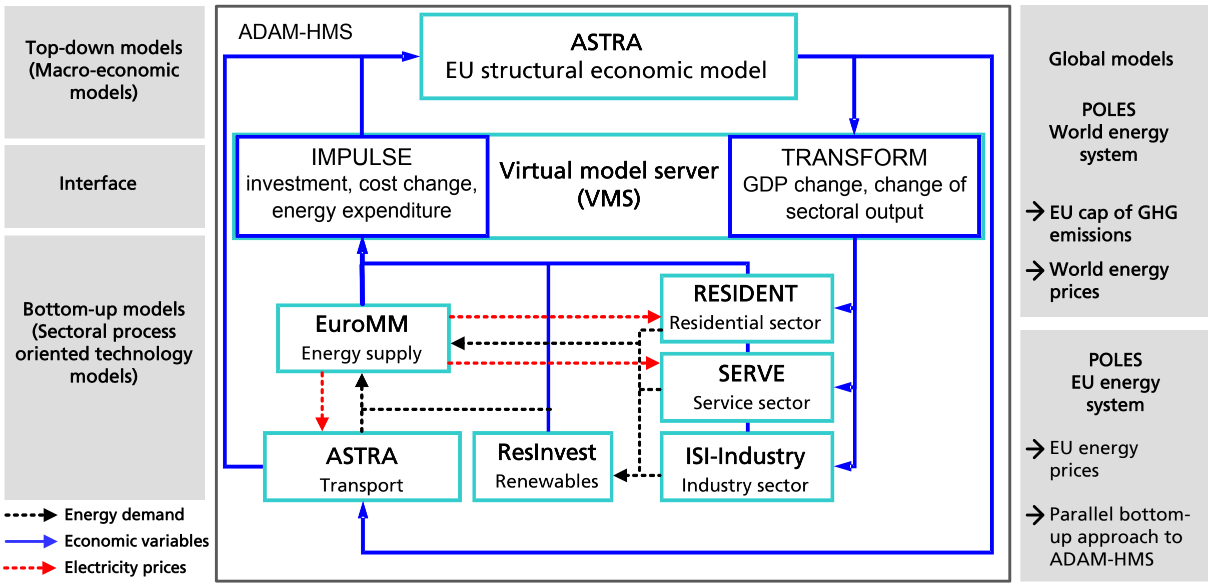

Figure 5-9 ADAM hybrid model system (HMS), POLES parallel approach and global framework
Source: Adapted from Jochem et al. (2009, p. 22)

To determine the overall gross electricity demand, the net electricity demand provided by the bottom-up models for the industry, service, residential and transport sector have to be taken into account as well as the auto-consumption of the energy sector and potential transmission and distribution losses. Therefore, PowerACE-ResInvest estimates endogenously the gross electricity demand based on formula (5.11). Multiplication factors used are based on information provided by the model EuroMM.

$$ele\_gross_k(t) = ele\_net_k(t) \cdot (1 + f\_auto_k + f\_trans_k)$$

$$ele\_net_k(t) = ele\_net\_ind_k(t) + ele\_net\_res_k(t) + ele\_net\_ser_k(t) + ele\_net\_tra_k(t) \tag{5.11}$$

where:

$ele\_gross_k(t)$	*Gross electricity demand in country k in year t*
$ele\_net_k(t)$	*Net electricity demand in country k in year t*
$ele\_net\_ind_k(t)$	*Gross electricity demand in the industry sector in country k in year t*
$ele\_net\_res_k(t)$	*Gross electricity demand in the residential sector in country k in year t*
$ele\_net\_ser_k(t)$	*Gross electricity demand in the service sector in country k in year t*
$ele\_net\_tra_k(t)$	*Gross electricity demand in the transport sector in country k in year t*
f_auto_k	*Factor to calculate the auto consumption in the energy sector in country k*
f_trans_k	*Factor to calculate the transmission and distribution losses in country k*

5.11 Summary and discussion

This chapter describes the ABS model PowerACE-ResInvest, which is developed to depict investment decisions in RET in the EU's electricity sector. The developed ABS model is able to reflect some key characteristics of the situation in real energy markets including the existence of individual, autonomously acting agents pursuing different strategies. A heterogeneous agent structure is implemented focussing on investment planner agents and government agents. Investment planner agents are characterised by different risk attitudes and technology preferences, whilst government agents are distinguished according to the policy instrument applied to support an increased use of RET in the electricity sector. In addition, government agents are exemplarily designed such that they dynamically respond to certain developments of the environment. Cost-resource curves are adapted to the requirements of a multi-agent simulation in order to integrate the detailed techno-economic characteristics of RET. The model simulates two exemplary price formation procedures for statistical transfers as the main cooperation measure implemented in the Renewables Directive 2009/28/EC. Summarising, the developed model enables the analysis of how the heterogeneity of investment planner agents and their specific behaviour influences the diffusion of RET and it provides an adequate instrument for the analysis of different policy options for the support of RES in the electricity sector.

Reflecting critically the developed modelling approach, several limitations can be identified. The first issue relates to the agents' design implemented in the model. Taking into account that no severe definition on the term 'agent-based simulation' exists, it should be considered that PowerACE-ResInvest incorporates the characteristics of an agent-based model, as identified by Wooldridge & Jennings (1995), to a certain extent. Thus, communication or social interaction between agents is represented only in a simplified way by the exchange of information on the measures, the agents plan to realise.

A dynamic adaptation of the actors' strategies in terms of learning algorithms is not considered in the model[46]. As outlined by Sensfuss (2008, p. 45) the parameter setting for the learning algorithms represents a challenging task and may considerably influence simulation results.

In general, ABS models tend to show weaknesses regarding their empirical foundation (Fagiolo et al. 2006; Fagiolo et al. 2007). Similarly, the quantification of the agents' characterisation is characterised by limited empirical support due to missing data availability. This refers in particular to the classification of the investment planner agents, a process which is notably challenging due to the wide geographical scope of the developed simulation model[47]. Insufficient data availability in particular regarding the characteristics of commercial actors including capital availability and structure as well as their main strategies on EU level is one of the reasons, why the agents’ design is hardly empirically supported. Instead, the agents

46 For an example of integrating learning algorithms into agent-based electricity market models, the reader is referred to Weidlich (2008).

47 To the knowledge of the author most of the ABS models that use empirically calibrated input data have a considerably smaller geographical scope. For instance Schwarz & Ernst (2009) consider a small region in Southern Germany covering roughly 13,000 km^2.

are designed such that the range of parameters reflects realistic values as much as possible. Due to insufficient data availability with regard to investment planner agents, the author abstained from a representation of a high number of actors in the model and implemented a restricted number of agent categories instead. In addition, the model runtime turned out to be highly sensitive to the number of investment agents defined.

Another point for criticism can be seen in the strictly sequential procedure, the investment planner agents follow to realise investment decisions. Therefore, it is supposed that the most innovation-oriented actors consider investments in renewable projects consistently earlier than laggards. However, one could imagine that in reality there might be investment planner agents characterised by less innovation-friendliness considering an investment before agents disposing of higher innovative capabilities for some reasons.

Regarding existing interdependencies with the conventional power sector, PowerACE-ResInvest is embedded into a hybrid modelling system (HMS) where the subsectors of the energy system are modelled by different bottom-up models including an optimising energy model in an iterative procedure. However, the time resolution used by the optimising energy model corresponding to six time-slices (three seasons and day and night) may be increased in particular if high amounts of fluctuating RES-E are integrated into the electricity system. The separate consideration of investment decisions in RET can be justified with the particular political framework conditions for RET including the provision of privileged access to the grid. This fact may reflect the real situation quite well for the near future, but assuming an increasing competitiveness of RET this may no longer apply for the long term up to 2050. Owing to the sectoral perspective of the simulation model, the direct impacts of an enhanced development of RET on electricity prices are not endogenously modelled by PowerACE-ResInvest. Instead, potential consequences of using RET are accounted for indirectly by the iterative modelling procedure in the context of the HMS.

Looking at the implementation of the price formation procedure for statistical transfers, it should be taken into account that the procedure is implemented without taking into account potential feedbacks on the prices of TGC and on the dynamic tariff setting procedure of FIT.

Moreover, it should be considered that the future development of RET in the electricity sector is subject to manifold uncertainties considering a long-term development. One option to account for these uncertainties would be the consideration of stochastic programming[48]. Though, the quantification of required input parameters including e.g. the expected value and the standard deviation represent a challenging task. Instead, following the proposition of Riahi et al. (2007) to deal with the high degree of uncertainties the long-term future of RET in the European electricity system is investigated using alternative scenarios with its main assumptions reflecting different climate change futures (see section 6.1). Riahi et al. (2007) identify emission drivers such as population, income and technological development, as the main uncertainties for policy makers and the setting of the political framework as the most relevant uncertainty for investors in the context of long-term climate change scenarios.

48 For an example of how stochastic programming can be integrated into energy system analysis the reader is referred to Göbelt (2001).

Dynamic technological development is integrated into the simulation model PowerACE-ResInvest based on the concept of experience curves assuming that electricity generation costs of a technology decrease with an increase of cumulative capacity. Though, one should take into account the limitations of this approach. These include the fact that the experience curve approach neglects changes in raw material prices, as e.g. steel for wind turbines or silicon for PV power plants, and their impact on electricity generation costs. An amplification of the experience curve concept which is referred to as the ‘two-factor learning curve’ separating the causes for cost reductions into learning-by-doing – represented by the cumulative capacity – and learning-by-searching – measured by expenditure for research and development (R&D) – is not implemented in PowerACE-ResInvest[49]. Finally, it should be considered that the technological development in particular of less mature RET such as wave energy plants still is difficult to predict.

49 For a detailed discussion on the role of technology learning and R&D activities the reader is referred to Barreto & Kemp (2008).

6 Model based analysis of investment decisions in the European renewable energy sector

This chapter presents the results of a scenario analysis realised based on the newly developed simulation model PowerACE-ResInvest. The simulation draws on data input resulting from the cost-resource curves, which have been derived as described in chapter 4. It is the objective of this chapter to show how potential future pathways on the diffusion of RET in the EU electricity sector could look like and how the different existing policy option influence the development of RET. Additionally, detailed quantitative information on the involved investments and policy costs is provided. The main focus is put on analysing the implications of national renewable support schemes including FIT and quota obligations. Furthermore, potential price indications for statistical transfer of renewable electricity between countries resulting from international trading mechanisms are analysed.

The chapter is organised as follows. The key framework assumptions and definitions of the scenarios are described in a first step. Then, the results from the analysis are presented in detail for each scenario followed by a discussion of the sensitivity of modelling results to variations in selected input parameters. The chapter closes with a discussion and a comparison of all scenario results.

6.1 Definition of Scenarios

To take into account interactions of RET with the remaining electricity system, the scenarios analysed in this thesis draw on climate change mitigation and adaptation scenarios that have been developed in the project 'ADAM' (see also section 5.10). Thus, the final electricity demand used in PowerACE-ResInvest is estimated using demand-models depicting the residential, service, transport and industry sectors in minute detail. This data is provided by partners of the ADAM project consortium. Reference lectricity prices are taken from ADAM scenario results obtained by POLES, a global sectoral model of the energy system (cf. Hulme & Neufeldt 2010, p. 402).

Four main scenarios are analysed, including a Reference Scenario, which assumes the application of only moderate climate change mitigation policies. This Scenario serves as reference for comparison. In the Reference Scenario the application of modest policy support in terms of a quota obligation with a moderate quota target for the share of renewables in electricity consumption is assumed. The other three scenarios assume the implementation of intensified policy measures to combat climate change, restricting global average temperature increase to 2°C by the end of this century. Besides a trading scheme with a CO_2 emission allowance trading scheme and sectoral policy measures in the demand sectors, sectoral support for RET in the electricity sector by means of FIT or quota obligations are assumed to be in place. In turn, these scenarios are distinguished according to the type of renewable energy support scheme applied. Whilst in one of the policy scenarios, it is supposed that all EU countries use a quota obligation to foment the development of RET in the electricity sector, the EU MS implement FIT systems in the other two policy scenarios. The two latter scenarios differ by the fact that governments are capable to adapt the policy design dynamically during the modelling period in one of the scenarios, whereas FIT are assumed to be static in the last policy scenario. This differentiation is made in order to analyse the impact of dynamically acting government agents.

Annual targets for the share of RES-E in electricity consumption, setting the political framework conditions for the modelling exercise, are considered for the implementation of the policy measures. Since the latest official EU-targets for the use of RES have been determined for the share of RES in final energy consumption in the absence of a specification for the electricity sector, it is assumed that interim targets in terms of the RES-E share are based on scenario results obtained from the European project 'EmployRES' (cf. Ragwitz et al. 2009).

Table 6-1 provides an overview of the four main scenarios analysed in this thesis and describes the main assumptions made. Subsequently, the assumptions made in these four scenarios are described in more detail.

Table 6-1 Overview on scenario assumptions for the model-based analysis

Scenarios	**Assumptions**
Reference	– Continuation of modest support policies in terms of a quota obligation – Electricity demand and prices based on the ADAM Base Case
Policy_Quota	– Intensified policy support in terms of quota obligation – Electricity demand and prices based on the ADAM 2°C Scenario
Policy_FIT_Dynamic	– Intensified policy support in terms of FIT – Dynamic tariff adaption active – Electricity demand and prices based on the ADAM 2°C Scenario
Policy_FIT_Static	– Intensified policy support in terms of FIT – Static FIT – Electricity demand and prices based on the ADAM 2°C Scenario

Source: Own illustration

Besides the scenarios described in Table 6-1, the potential impact of climate change on electricity generation in hydropower plants is illustrated. In this context, it is shown how climate-related alterations in river discharge regimes may affect investment decisions in hydropower capacity.

6.1.1 Reference Scenario

The Reference Scenario builds on assumptions made for the Base Case Scenario analysed in the ADAM project. The ‘ADAM Base Case Scenario’ represents an explorative scenario, assuming the implementation of moderate and constant policy trends in energy policy, whilst no climate change effects are assumed to occur before 2050 (Jochem et al. 2007, p. 7). This means that no emission reduction targets or climate change adaptation measures in addition to the existing ones are active. Since the combination of only moderate climate mitigation efforts without assuming the occurrence of climate change effects does not reflect a realistic future development, the 'ADAM Base Case Scenario' represents rather a virtual scenario than a realistic projection. Similar to the 'ADAM Base Case Scenario', the Reference Scenario developed in this thesis serves as a reference scenario for comparison. It reflects conservative assumptions on the implementation of sectoral mitigation policies not only in the renewable energy sector and in the different demand sectors as well as cross-sectoral policies such as emission trading. Table 6-2 provides an overview of the key assumptions made for the development of gross electricity demand, reference electricity prices and RES-E targets.

Table 6-2 Key assumptions for gross electricity demand, reference electricity prices and annual targets for RES-E in the Reference Scenario

	2005	2010	2020	2030	2040	2050
Gross electricity demand [TWh]	3,266	3,342	3,566	3,788	3,869	3,902
Reference electricity prices [$€_{2005}$/MWh]	56	49	47	48	49	51
Annual RES-E targets	15%	19%	23%	28%	28%	28%

Source: Assumptions partly based on Jochem et al. (2007) and Ragwitz et al. (2009). Net electricity demand has been converted to gross electricity demand taking into account transmission and distribution losses and electricity consumption of the energy sector. In case of reference electricity prices, the EU average weighted according to national electricity demand is shown.

According to results of the 'ADAM Base Case Scenario' – estimated by the bottom-up demand models ISI-Industry, RESIDENT, SERVE and ASTRA-Transport – gross electricity demand is assumed to increase by 19 % from 3.3 PWh in 2005 to 3.9 PWh by 2050 (see Table 6-2). With regard to reference electricity prices, a very moderate price development until 2050 is assumed.

With regard to the policies in place in the renewable energy sector, it is supposed that a quota obligation is applied by all EU MS. The respective targets for the share of RES in total electricity demand are taken from a baseline scenario of modelling results simulated with the model Green-X in the context of the project 'EmployRES', as shown in Table 6-2. Given the moderate development of RES-E and the relevance of the electricity sector for target achievement the EU is unlikely to meet the 2020 targets in the Reference Scenario. Accordingly, the assumed target for the share of renewables in gross electricity consumption increases slightly from 15 % in 2005 to 23 % by 2020 and 28 % by 2030.

It should be noted that the RES-E development simulated with PowerACE-ResInvest does not necessarily match the predetermined target. On the one hand targets may not be achieved, if there is not sufficient potential available or other existing barriers impede target fulfilment. On the other hand the RES-E share simulated with PowerACE-ResInvest may also exceed targets, e.g. if a considerable amount of low-cost RET potential is available. If no financial support is available or if the certificate price drops to zero, the reference electricity price represents the possible revenue per unit of renewable electricity generated.

6.1.2 Policy Scenarios

The policy scenarios realised in this analysis are based on the 'ADAM 2° Scenario', assuming that temperature increase by end of the century is limited to 2°C above preindustrial level as a consequence of intensified mitigation options in the energy sector. Given the uncertainty range of climate sensitivity to GHG concentration levels, different stabilisation scenarios are associated to the 2°C target according to the probability of target achievement. Thus, stabilising the level of GHG emissions at 450ppm CO_2 equivalent is expected to involve a 50 % probability of meeting the 2° C target, whilst a stabilisation level of 400ppm CO_2 equivalent limits temperature increase to 2°C with a likelihood of approximately 80 % (Hare & Meinshausen 2006). From both 2°C Scenario variants assuming a CO_2 equivalent target concentration of 400ppm and 450ppm that have been explored in the context of the ADAM project, the 450ppm Scenario Variant has been selected. Although the investigations of the ADAM project have shown that both 2°C Scenario Variants appear to be feasible from a technological point of view, additional socio-political constraints may jeopardise the achievement of climate change targets. In this context, it is assumed that achieving a CO_2 target of 450ppm already implies a high ambition level and is considered to be more realistic than the 400ppm Scenario Variant. The key assumptions made for the three policy scenarios are depicted in Table 6-3.

Table 6-3 Key assumptions for gross electricity demand, reference electricity prices and annual targets for RES-E in the Policy Scenarios

	2005	**2010**	**2020**	**2030**	**2040**	**2050**
Gross electricity demand [TWh]	3,266	3,254	3,177	3,071	2,837	2,591
Reference electricity prices [€$_{2005}$/MWh]	52	60	77	81	81	79
Annual RES-E targets	15%	20%	32%	49%	49%	49%

Source: Assumptions partly based on Jochem et al. (2007) and Ragwitz et al. (2009). Net electricity demand has been converted to gross electricity demand taking into account transmission and distribution losses and electricity consumption of the energy sector. In case of reference electricity prices, the EU average weighted according to national electricity demand is shown.

Given that intensified policy measures are in place in order to increase energy and material efficiency in the demand sectors, results from the '2° Scenario' (450ppm) indicate a potential reduction of gross electricity demand by approximately 20 % until 2050 against the base year 2005 (see Table 6-3). Accordingly, gross electricity demand by 2050 is estimated to amount to 2.6 PWh corresponding to only two thirds of the electricity demanded in the same year assumed in the Reference Scenario of this thesis.

Renewable energy support policies are implemented differently throughout the three policy scenarios, but they all draw on the same targets for the share of renewables in electricity consumption. The targets draw on the policy scenario of the project 'EmployRES'. Assuming a favourable development of renewables in the heat and transport sector, the targets in the policy scenarios are sufficient to meet the final energy targets set for 2020. Targets for the share of renewables in electricity consumption increase to 32% by 2020 and to approximately 49 % by 2050.

Policy_Quota Scenario

In case of the Policy_Quota Scenario, all governments are supposed to use a quota obligation to support RET in the electricity sector. In contrast to the quota obligation applied in the Reference Scenario national targets are more ambitious, as shown in Table 6-3.

Policy_FIT_Dynamic Scenario

This Scenario intends to analyse the impacts of intensified policy measures using FIT systems. In particular, the impact of the dynamic behaviour of the government agents in terms of an adaptation of the support conditions will be analysed.

It is assumed that the initial values of the FIT correspond to the financial support currently available as described by (Coenraads et al. 2008a). FIT are differentiated on a country and technology level. In countries using currently quota obligations with TGC, the sum of the average reference electricity price and the average price of the TGC are taken as the level of the hypothetical FIT in this country. If no financial support is available for a certain technology in a country, the reference electricity price represents the possible revenue per unit of renewable electricity generated. In this scenario only the FIT for the base year 2005 represent an exogenous data input. Then, the government agents decide individually whether they adapt tariffs according to the degree of target achievement, which is taken from the Green-X policy scenario computed in the context of the 'EmployRES' project (see Table 6-3).

Policy_FIT_Static Scenario

Similar to the previously described Policy Scenario assuming dynamic FIT systems to be active, this scenario provides the basis for comparison required to analyse the effects of the dynamic behaviour of the government agents. Therefore, the application of FIT for all EU-countries is assumed as described for the Policy_FIT_Dynamic Scenario. In contrast, tariffs remain at a constant level throughout the overall modelling horizon.

6.2 Results

6.2.1 Reference Scenario

Figure 6-1 shows the development of RET in the EU electricity sector under Reference conditions from 2005 to 2050 as computed with the model PowerACE-ResInvest. Even in the Reference Scenario, the use of RET is expected to increase considerably between 2005 – when 167°GW of RET-capacity were installed – and 2050. About 460 GW of renewable electricity generation capacity are expected to be installed in total until the mid-century and to be able to produce 1,422 TWh annually. About 36 % of the EU's electricity demand by 2050 can be provided based on RET. However, a RES-E share of 24 % that is achieved until 2020 appears to be insufficient to meet the 2020 targets, taking into account the relevance of the electricity sector for target achievement. Although the quota target is not increased after 2030, growth of RET continues at slower pace.

In terms of the technology mix, it can be observed that hydropower represented the dominating RET in 2005, but the dynamic wind development converts wind in the leading RET until 2050. Since the hydropower potential is nearly exploited so far in particular in Western European countries, this technology only shows moderate growth. The share of biomass technologies including solid biomass, biowaste and biogas in total RET-contribution remains constant at 15 %. Cost-intensive technologies such as Solar PV only make minor contributions to total renewable electricity generation.

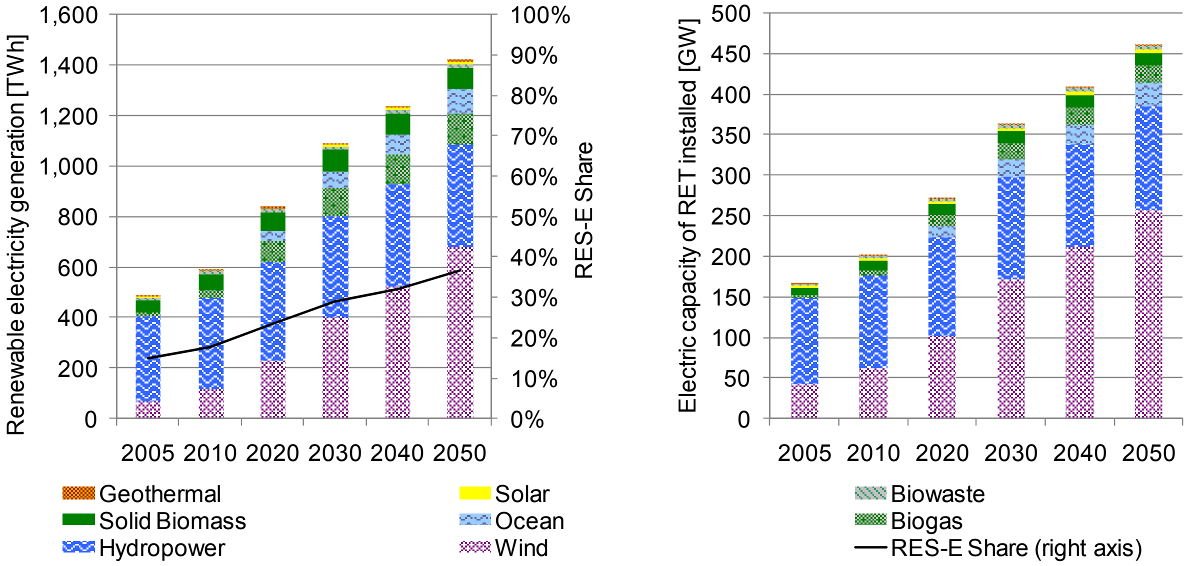

Figure 6-1 Renewable electricity generation, the share of renewables in gross electricity consumption and installed renewable capacity between 2005 and 2050 in the Reference Scenario

Source: Own illustration based on scenario runs with PowerACE-ResInvest

The installed RET-capacity development as shown in Figure 6-1 involves a total investment of 791 billion Euro, taking into account the investments made from 2005 until 2050. This investment includes investment for the replacement of all renewable power plants constructed during the simulation period and the renewable power plants constructed before the base year 2005. Cumulative investments aimed at the additional construction of renewable power plants between 2005 until 2050 amount to 354 billion. The specific investment per unit of installed and refurbished RET capacity decreased from 1,716 €/kW in 2006 to 1,188 €/kW until 2050 as a consequence of technology learning and a changing RET portfolio.

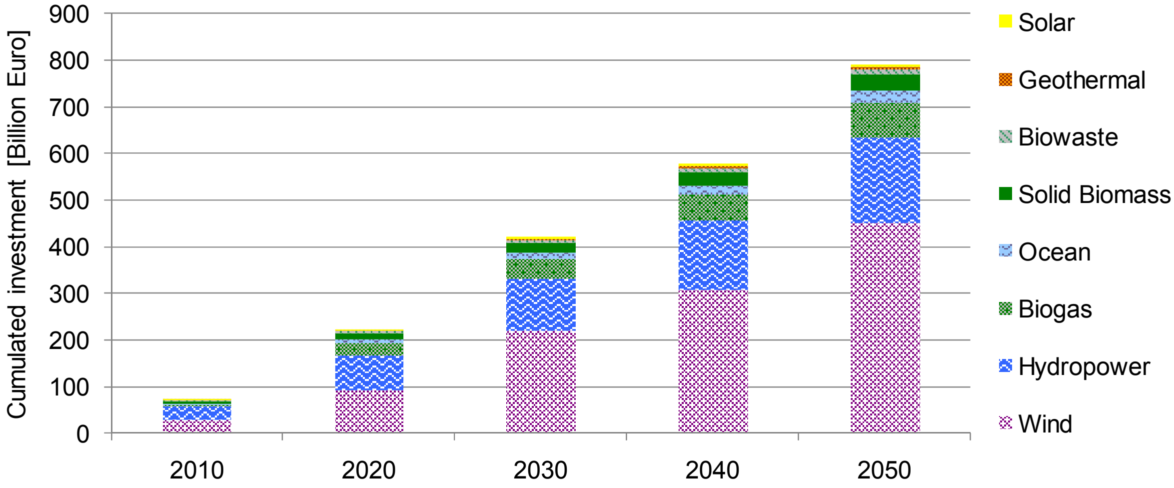

Figure 6-2 Cumulated investment into renewable electricity generation technologies to 2050 in the Reference Scenario. Investment required for the replacement of all renewable power plants is included

Source: Own illustration based on scenario runs with PowerACE-ResInvest

Besides the investment required to stimulate the development of RET in the Reference Scenario, it is analysed what this development means for average financial characteristics per unit of renewable electricity generated. Figure 6-3 shows the development of the policy costs or the weighted average of all national TGC prices, the total remuneration corresponding to the sum of the reference electricity price and the TGC price, and the average electricity generation costs of the additionally installed RET capacity.

The development of average certificate prices, as depicted by the light blue line in Figure 6-3, starts at a comparatively high level of 133 €/MWh and drops to values of less than 10 € during the period after 2040. In addition, the certificate price development shows a high volatility in particular in the period from 2015 to 2030. Thus, certificate price building mechanisms appear to be very sensible towards the predetermined quota targets. Average electricity generation costs of additionally installed capacity range between 42 €/MWh in 2037 and 87 €/MWh in 2026 and show therewith considerably less fluctuations than the support level. Due to the strong development of onshore wind power plants, average electricity generation costs are mainly determined by this technology.

After 2030 the average remuneration level predominantly corresponds to the reference electricity price, as certificate prices are on a very low level. Despite the excess in renewable electricity generation regarding the predefined targets on EU level, the average certificate price assumes values above zero, since some countries such as Austria, Belgium, Finland or Portugal miss their national targets during several years in the time horizon after 2032.

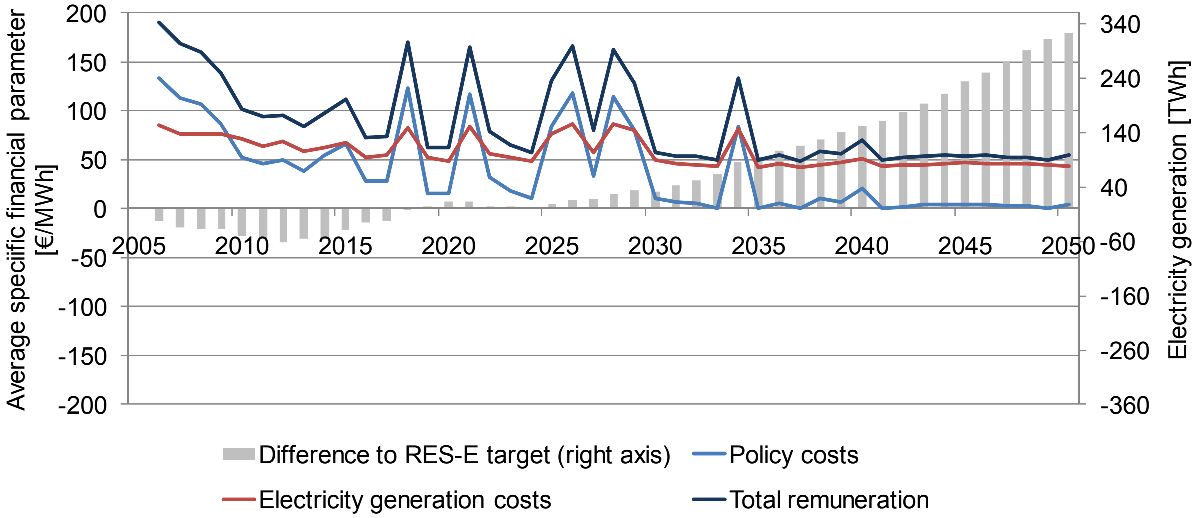

Figure 6-3 Average financial parameters per unit of electricity generated including policy costs, average electricity generation costs of additionally installed capacity, average total remuneration and the difference towards annual target achievement in generation terms in the Reference Scenario

Source: Own illustration based on scenario runs with PowerACE-ResInvest

6.2.2 Policy_Quota Scenario

Due to a more ambitious target level the future development of RET in the electricity sector in the Policy_Quota Scenario conditions is expected to increase stronger than in the Reference Scenario (see Figure 6-4 and Figure 6-1). According to the scenario calculations, an installed capacity of renewable power plants amounting to 600 GW is estimated to produce 1,699 TWh of renewable electricity by 2050. The evolution of renewable electricity generation shows rapid growth in particular in the period from 2010 to 2030. Growth of RET in the electricity sector appears to be restricted by non-economic limitations such as the manufacturing capacity before 2010, whilst no longer increasing targets for the RES-E share slow down development after 2030. The manufacturing capacity is extended during the modelling horizon involving therewith an accelerated RET development between 2010 and 2030.

Looking at the potential contribution of RET to cover the EU's electricity demand, the scenario run estimates that 66 % of the electricity demanded in 2050 can be provided from RET. The fact that wind power plants are supposed to supply 33 % of total gross electricity consumption poses important challenge for the integration of fluctuating wind power in the electricity grid. Results from an analysis realised using the hybrid bottom-up modelling approach – as described in section 5.10 – indicate that a RES-E share of 75 % appears to be manageable by reinforcing the grid infrastructure, utilising back-up capacities and energy storage technologies such as pumped storage of hydropower, and by enabling international electricity trade (Schade et al. 2009, pp. 253-263). However, it should be noted that additional analysis taking into account a higher temporal resolution than the six time-slices (three seasons and day and night) as used by the optimising energy model EuroMM would be required to make a final assessment on the issue of handling such high shares of renewables in the electricity mix.

Similar to the development in the Reference Scenario, wind power dominates the renewable electricity mix in particular towards the end of the considered modelling period. Solar power still makes a minor contribution to total renewable-based electricity supply by producing 31 TWh by 2050. This represents at least an increase compared to solar electricity generation in the Reference Scenario, where solar power plants are expected to produce only 9 TWh of electricity.

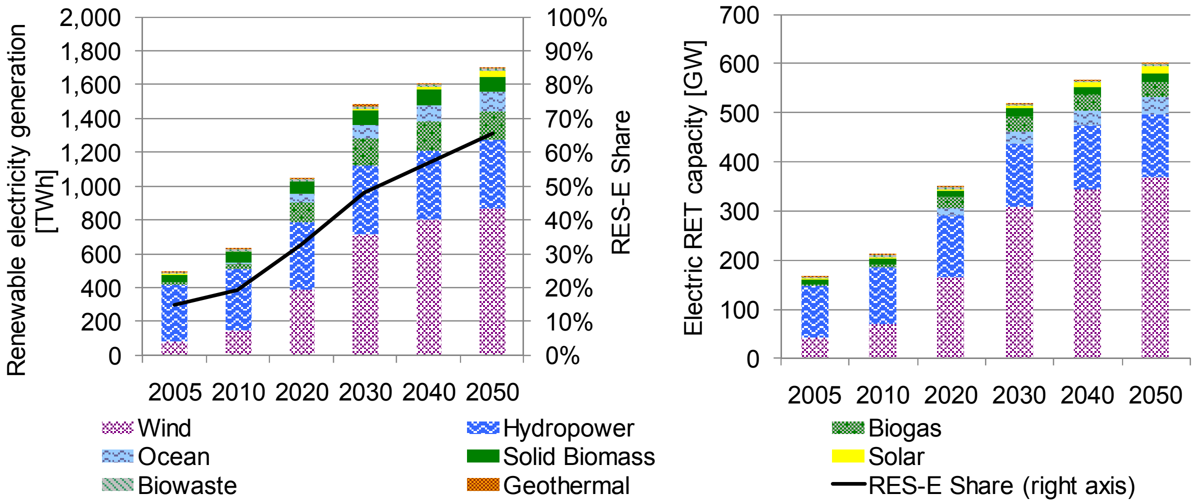

Figure 6-4 Renewable electricity generation, the share of renewables in gross electricity consumption and installed renewable capacity between 2005 and 2050 in the Policy_Quota Scenario

Source: Own illustration based on scenario runs with PowerACE-ResInvest

The cumulated investments required to stimulate the RET development in the Policy_Quota Scenario amount to 1,123 billion euro between 2005 and 2050 (see Figure 6-5), whereof 528 billion euro are used to build additional renewable capacity. Specific investment in new and refurbished capacity is thereby supposed to decrease from 1,716 €/kW in 2006 to 1,163 € in 2050. Comparing the investment in the Policy_Quota Scenario with those in the Reference Scenario, additional investments of 331 billion euro have been made.

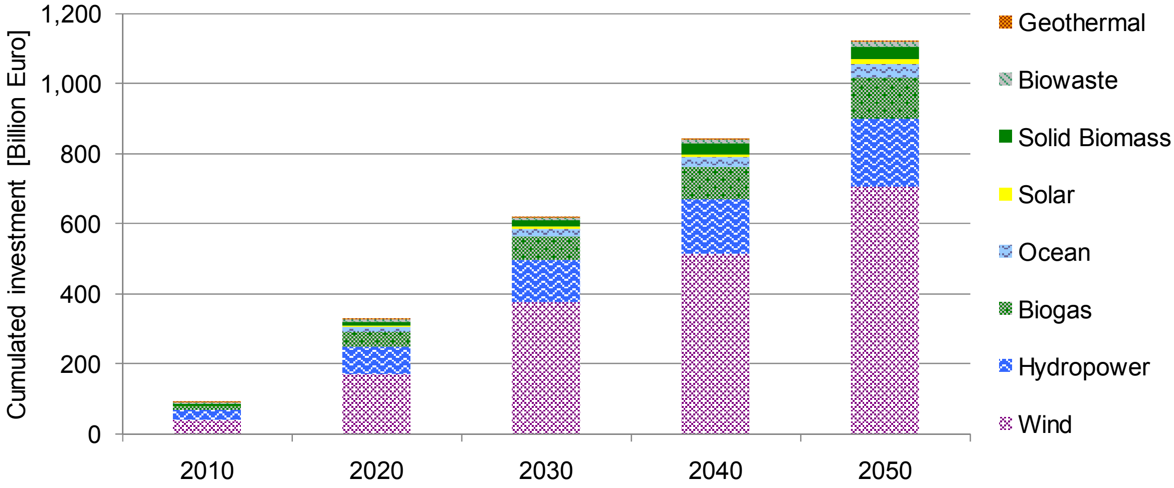

Figure 6-5 Cumulated investment into renewable electricity generation technologies to 2050 in the Policy_Quota Scenario. Investment required for the replacement of all renewable power plants is included

Source: Own illustration based on scenario runs with PowerACE-ResInvest

The development of the policy costs or the TGC price starts on a comparatively high level of about 119 €/MWh as a consequence of missing manufacturing capacity of least cost RET (see Figure 6-6). The decreasing trend of the certificate price until 2010 can be explained by an increase in manufacturing capacity of low-cost technologies and an improving degree of target achievement.

Then, the TGC price remains on a constant level for the following four years whilst the difference to the RES-E target increases. After a period of target over-fulfilment between 2018 and 2023 the certificate price increases again due to problems with regard to achievement of quota targets. Evidently, average policy costs for renewable electricity decline to nearly 0 €/MWh after 2032, reflecting less ambitious targets, which remain on a constant level. Average electricity generation costs show less fluctuations than the total remuneration and the certificate price, but there are small peaks in the years of high certificate prices. During the last twenty years of the modelling horizon, average electricity generation costs of RET converge towards 60 €/MWh. For comparison, electricity generation costs of RET in the Reference Scenario range about 45 €/MWh during the same period.

Although the certificate price is close to zero in the time horizon after 2030, higher reference electricity prices than under Reference Scenario conditions provide a comfortable remuneration level for the renewable power plants that are installed. Due to the decreasing trend of the electricity demand (see Table 6-3), surplus electricity generation from RET increases considerably starting in 2032.

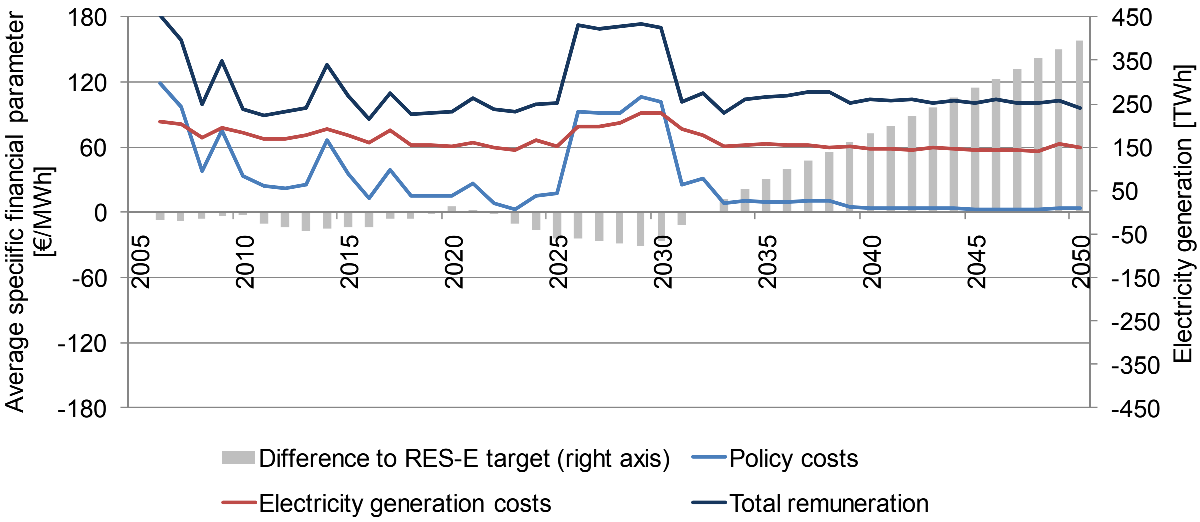

Figure 6-6 Average financial parameters per unit of electricity generated including policy costs, average electricity generation costs of additional RET capacity, average total remuneration and the difference towards annual target achievement in generation terms in the Policy_Quota Scenario.

Source: Own illustration based on scenario runs with PowerACE-ResInvest

6.2.3 Policy_FIT_Dynamic Scenario

Assuming the application of fixed FIT in all EU countries in combination with a dynamic tariff adaptation behaviour of the government agents, 1,906 TWh of electricity are estimated to be generated from 767 GW of renewable electric capacity by 2050 (see Figure 6-7). As targets only have an indirect impact on support conditions via the tariff adaptation mechanism, growth after 2030 is not dampened as much as in the Policy_Quota Scenario. According to the scenario runs RET may contribute roughly 73 % of the total EU's electricity supply by 2050 assuming that such a high share of RET in the electricity system can still be operated and handled. Additional analysis simulating the operation of the electricity system at high temporal resolution would be required to investigate whether such a high share of RET is feasible for the operation of the electricity system.

The technology mix in the Policy_FIT_Dynamic Scenario shows a considerably larger share of solar electricity than in the Policy_Quota Scenario. Whilst only 30 TWh of electricity are produced based on solar energy technologies in the Policy_Quota_Scenario, the support of FIT appears to induce a stronger use of solar energy with an annual production amounting to 210 TWh by 2050. The reason for this is the technology-specific character of the FIT, as it may enable higher support for technologies characterised by higher electricity generation costs. In contrast, the technology-neutral support as provided by the quota obligation focuses on the stimulation of low-cost technologies. Consequently, the market development of the technologies distinguished by high electricity generation costs starts to take place at a later stage if technology-neutral support schemes are applied.

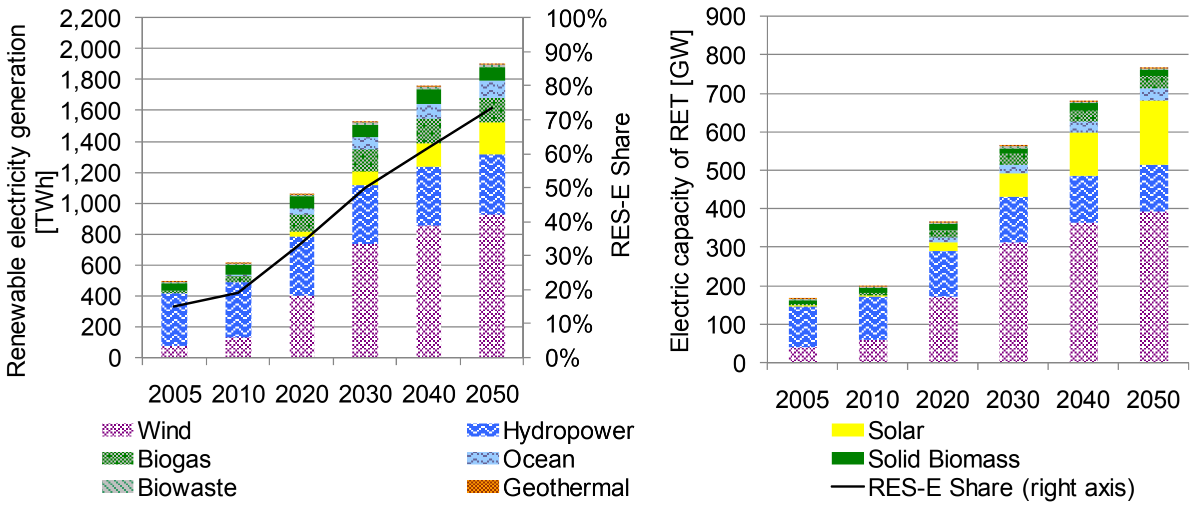

Figure 6-7 Renewable electricity generation, the share of renewables in gross electricity consumption and installed renewable capacity between 2005 and 2050 in the Policy_FIT_Dynamic Scenario

Source: Own illustration based on scenario runs with PowerACE-ResInvest

The development of RET as depicted in Figure 6-7 involves investments of 1,278 billion euro until 2050. As shown in Figure 6-8, most of the investment is made in wind power plants (728 billion Euro), but a considerable amount of 175 billion euro is invested in solar energy technologies. The average investment per unit of electric capacity additionally installed or refurbished decreases from 1,691 €/kW in 2006 to 1,085 €/kW by 2050. The reduction in the specific investment of the capital-intensive power plants in the Policy_FIT_Dynamic Scenario is only slightly stronger than in the Policy_Quota Scenario, as learning effects are assumed not to occur exclusively on European, but on global level.

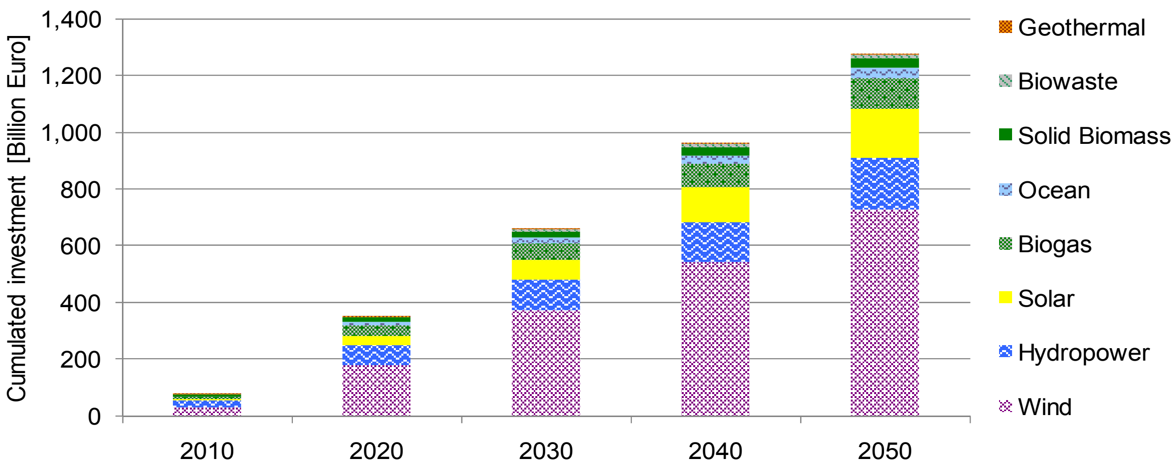

Figure 6-8 Cumulated investment into renewable electricity generation technologies to 2050 in the Policy_FIT_Dynamic Scenario. Investment required for the replacement of all renewable power plants is included

Source: Own illustration based on scenario runs with PowerACE-ResInvest

Observing Figure 6-9, it can be seen that policy costs in the Policy_FIT_Dynamic Scenario are characterised by a smoother development than in the scenarios assuming the application of a quota obligation. The level of policy costs starts at 26 €/MWh and increases up to 79 /MWh in 2017. Then, a reduction of the policy costs occurs shortly after 2017, coinciding with an increase of the surplus electricity generated regarding the target. Starting around 2031, the excess of renewable electricity generated implies that most of the government agents reduce FIT. The consequence is a decreasing trend of the policy costs, amounting to zero towards the end of the modelling horizon.

Average electricity generation costs from additionally installed capacity range from 68 €/MWh to 86 €/MWh. Thereby, average electricity generation costs remain on a rather constant level during the whole modelling horizon until costs of newly installed renewable power plants converge to roughly 69 €/MWh in 2050. For comparison, average electricity generation costs as observed in the Policy_Quota Scenario converges towards lower cost levels of about 60 €/MWh. Figure 6-9 shows that the gap between the total remuneration per unit of renewable electricity generated shows a decreasing trend between 2030 and 2050.

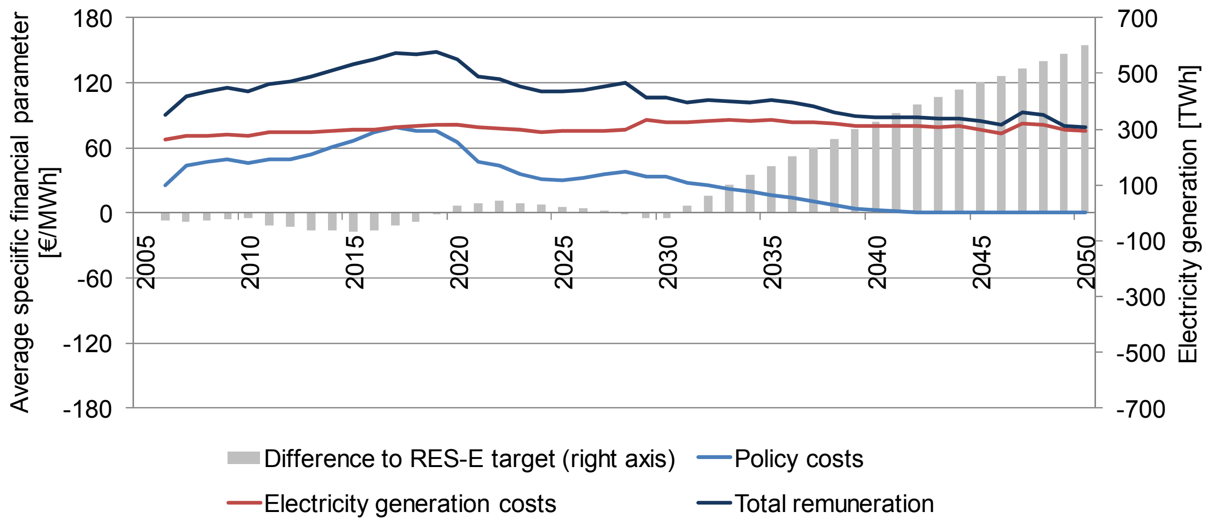

Figure 6-9 Average financial parameters per unit of electricity generated including policy costs, average electricity generation costs of additional RET capacity, average total remuneration and the difference towards annual target achievement in generation terms in the Policy_FIT_Dynamic Scenario

Source: Own illustration based on scenario runs with PowerACE-ResInvest

6.2.4 Policy_FIT_Static Scenario

Since renewable targets are not considered by government agents and FIT remain constant over the long period of 45 years, the RET development in the Policy_FIT_Static Scenario even exceeds that of the Policy_FIT_Dynamic Scenario. Assuming the application of static FIT, the simulation run indicates that 1,985 GWh of electricity can be produced from RET by 2050 corresponding to a RES-E share of roughly 77 % (see Figure 6-10). It should be noted, that additional analyses about the operability of an electricity system with such a high share of renewables are suggested.

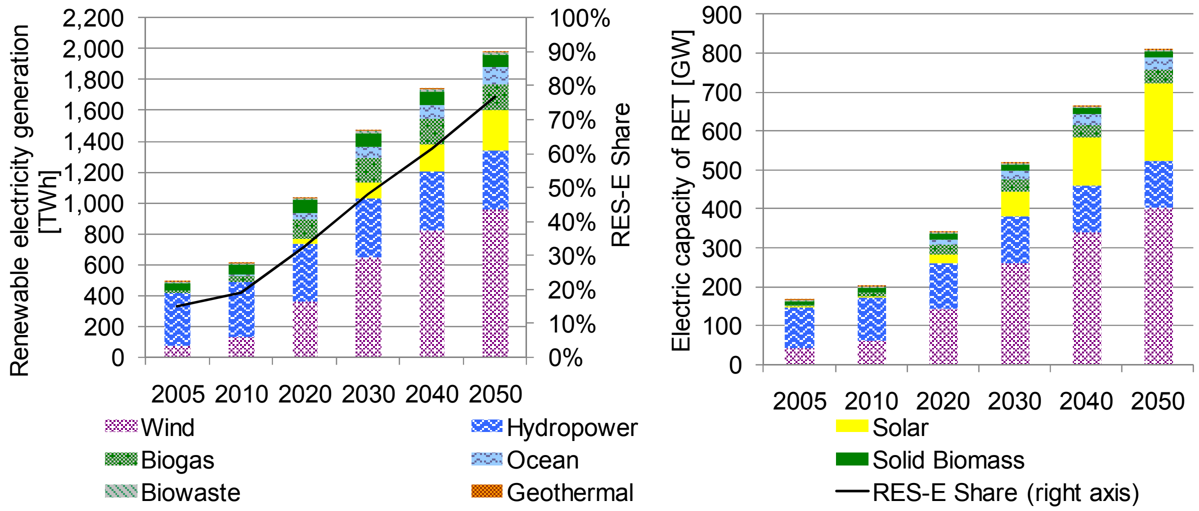

Figure 6-10 Renewable electricity generation, the share of renewables in gross electricity consumption and installed renewable capacity between 2005 and 2050 in the Policy_FIT_Static Scenario

Source: Own illustration based on scenario runs with PowerACE-ResInvest

The investment associated to the strong market development of RET in the electricity sector in the Policy_FIT_Static Scenario amounts to 1,273 billion € considering the period between 2005 and 2050 (see Figure 6-11). 687 billion € of investments are made in the Policy_FIT_Static Scenario to build additional renewable power plant capacity. Average investments per unit of electric capacity installed and refurbished are very similar to Policy_FIT_Dynamic Scenario and decrease from 1,691 €/kW in 2006 to 1,084 €/kW in 2050.

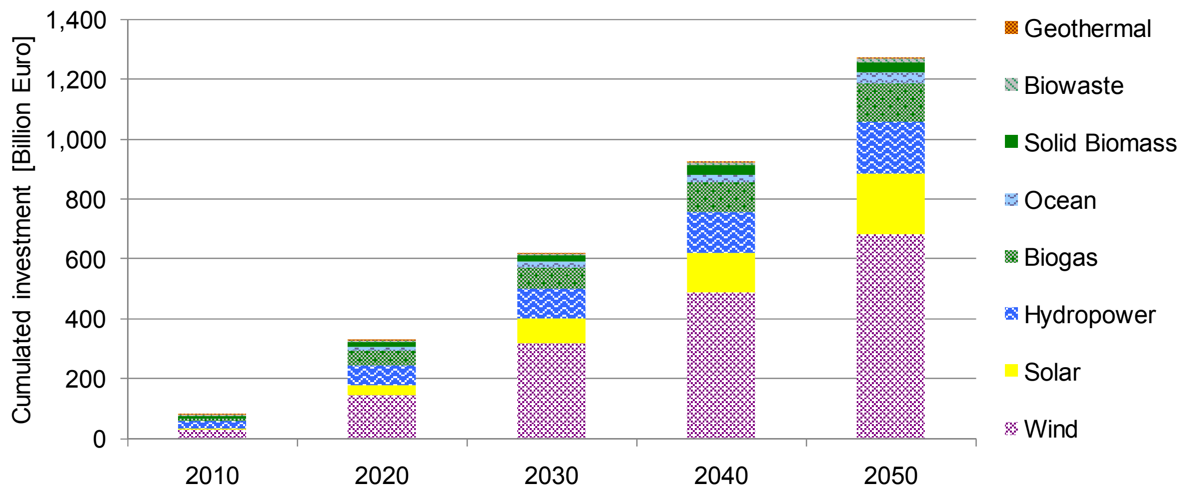

Figure 6-11 Cumulated investment into renewable electricity generation technologies to 2050 in the Policy_FIT_Static Scenario. Investment required for the replacement of all renewable power plants is included

Source: Own illustration based on scenario runs with PowerACE-ResInvest

Observing the main average financial parameter of the electricity generated from newly installed renewable capacity shown in Figure 6-12, the trend of the remuneration level and the policy costs is clearly upwards. The distinct divergence of the remuneration level and the average electricity generation costs indicates an excessive support level, amounting up to 271 €/MWh, and therefore to very high policy costs of 189 €/MWh by 2050. This can be explained by the high share of additional solar capacity installed in 2050 and the fact that the initially determined technology-specific FIT for solar PV remains unchanged on a high level without accounting for cost reductions. An even stronger increase of solar PV is restricted by non-economic limitations such as the existing manufacturing capacity.

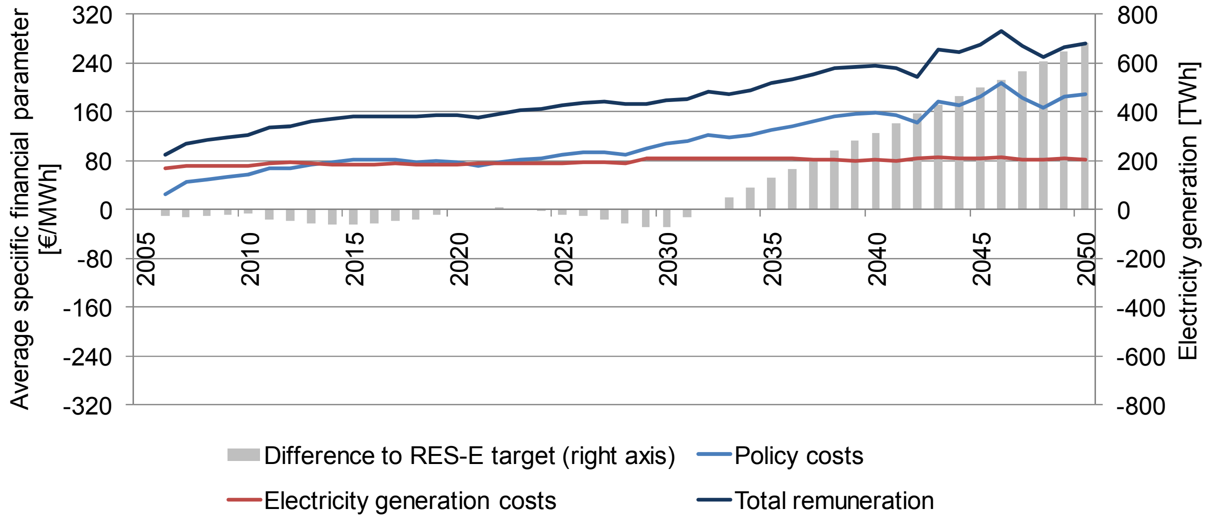

Figure 6-12 Average financial parameters per unit of electricity generated including policy costs, average electricity generation costs of additional RET capacity, average total remuneration and the difference towards annual target achievement in generation terms in the Policy_FIT_Static Scenario

Source: Own illustration based on scenario runs with PowerACE-ResInvest

6.3 Comparison of scenario results

Observing the comparison of scenario results in terms of cumulative electricity production (see Figure 6-1), it becomes clear that the diffusion of RET under Reference Scenario conditions remains below that of the three policy scenarios as a result of a lower ambition level of policy targets. Cumulated electricity generation from RET in all three policy scenarios follow a similar course until 2030, but show a difference in the technology mix. Assuming the implementation of FIT a stronger development of solar electricity occurs caused by the technology-specific renewable energy support. After 2030 the market diffusion of RET in the electricity sector starts to diverge in the three policy scenarios. Owing to a quick adaptation to the stagnating policy targets the lowest increase can be observed in the Policy_Quota Scenario. In contrast RES-E generation in the Policy_FIT_Dynamic and the Policy_FIT_Static Scenarios increases faster than in the Policy_Quota Scenario. The dynamic behaviour of the government agents implies a slightly stronger growth of RES-E up to 2030 than in case of constant FIT in the Policy_FIT_Static Scenario. During the last two decades considered in the scenario analysis cumulated electricity generation from RET in the Policy_FIT_Static Scenario exceeds that achieved assuming Policy_FIT_Dynamic assumptions.

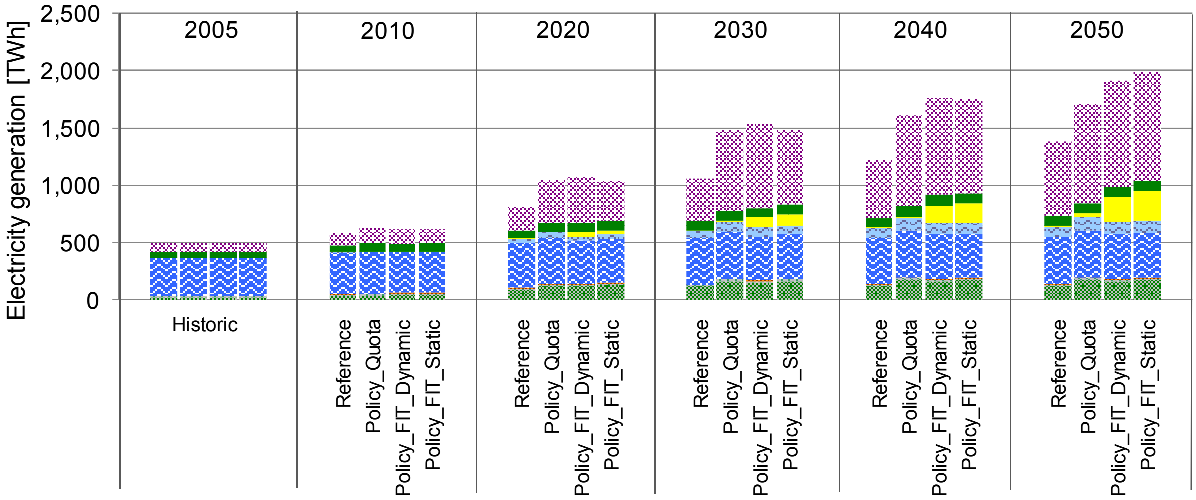

Figure 6-13 Comparison of electricity generation in all scenarios
Source: Own illustration based on scenario runs with PowerACE-ResInvest

The additionally installed renewable power plant capacity distinguished according to the responsible investment planner agent, as shown in Figure 6-14, shows stronger fluctuations in both scenarios where quota obligations are implemented. This development can be explained by the variable TGC prices. According to the simulation runs the 'Early Adopters' and the 'Early Majority' account for the dominant share of investments in renewable power plants in all four scenarios. Despite the fact, that the 'Early Majority' and the 'Late Marjority' have the same amount of capital available, the 'Early Majority' appears to invest considerably more than the 'Late Majority'. This difference is due to varying technology preferences of the investment planner categories. Differences in the evaluation of the project profitability are another reason for the different investment activity levels of both investment planner agents. Finally, it should be taken into account that the predetermined decision order of the investment planner agents influences the allocation of renewable power plants to the agent categories. This argument is supported by the fact that the less innovation-oriented agents including the 'Late Majority' and the 'Laggards' invest considerably less in case less additional capacity is installed in total. Comparing the electricity generation in the Reference Scenario characterised by a moderate additional capacity with both policy scenarios assuming the implementation of FIT, it becomes clear that the share of electricity generation in renewable power plants financed by the 'Late Majority' is considerably lower in particular in the time horizon until 2030 (see Figure 6-14). Thus, innovation-oriented agents exploit the available investment options before the remaining agents have a chance to decide on investments.

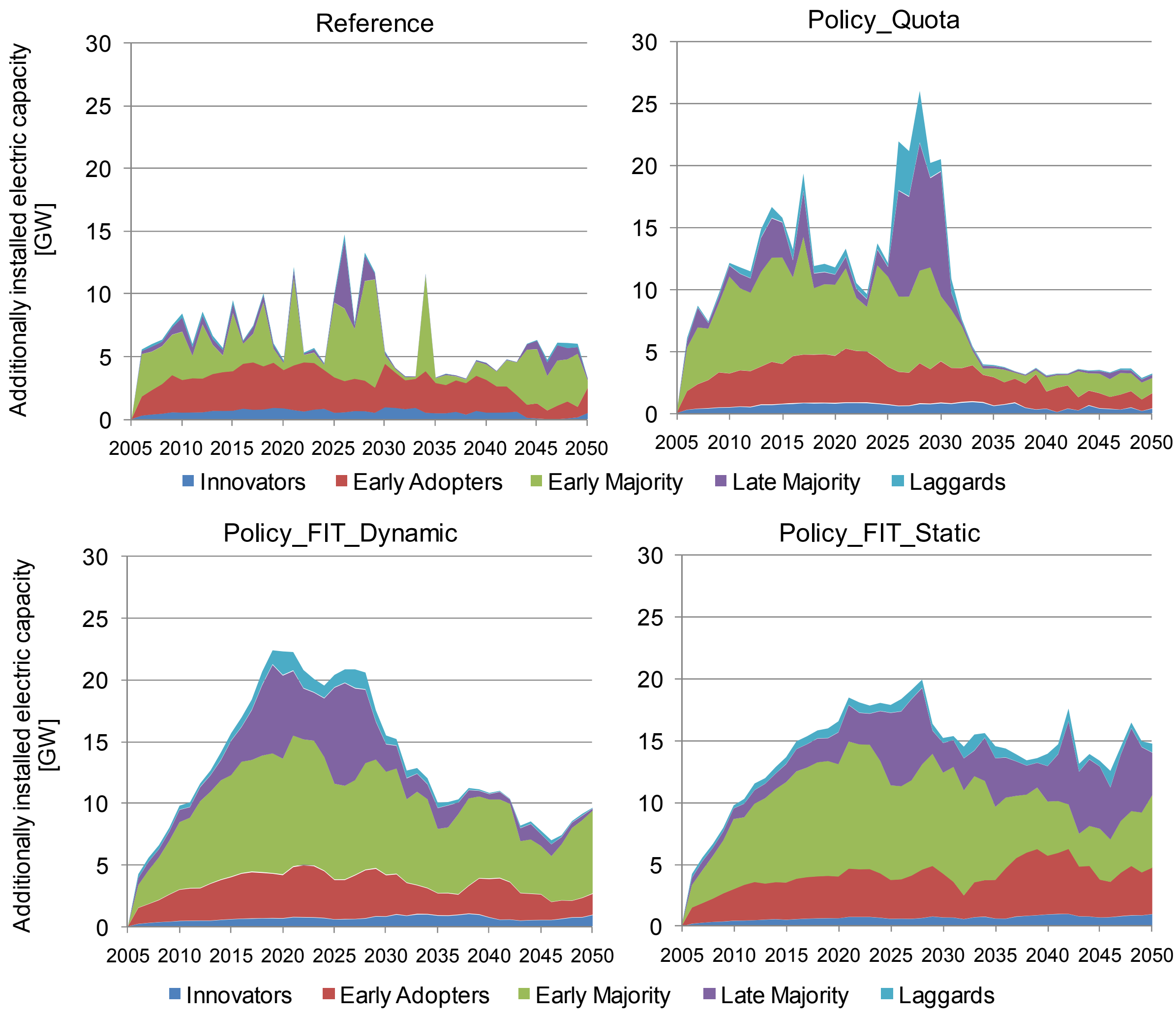

Figure 6-14 Annually installed electric capacity on agent-level in all four scenarios
Source: Own illustration based on scenario runs with PowerACE-ResInvest

Figure 6-15 depicts price indications for statistical transfers as simulated with PowerACE-ResInvest and defined in section 5.7.2. Price indications are reflected against the difference to RES-E targets in terms of electricity generation on EU level. Generally, it can be observed that the course of the price indications looks similar in those scenarios applying the same support instruments. Thus, price indications for statistical transfers in both quota obligation scenarios are characterised by a higher volatility than price indications in the FIT-based scenarios. The fact that the respective deviations from the RES-E target in the quota obligation scenarios are lower than in the other two scenarios indicates that quota obligations are better suited to meet a predetermined target, but tend to involve a high sensitivity to prices. Owing to a strong demand for the statistical import of RES-E in both quota scenarios until 2020, the price indication for statistical transfers from the perspective of potential importing countries is considerably higher than in the FIT scenarios. The latter scenarios are characterised by a moderate demand for statistical transfers until 2015 and a strong surplus supply afterwards. In contrast, transfer price indications resulting from the expectations of potential exporting countries appear to be higher in the FIT scenarios.

Comparing the course of both price indications, it becomes clear that in particular in the quota scenarios the demand-based price indication exceeds the supply-based price indication during most of the time horizon. Only in the period from 2019 to 2023 in the Policy_Quota Scenario and in several particular years in the Reference Scenario (2021, 2023 and 2024) the willingness-to-pay of potential importing countries is below the price level of potential sellers.

By contrast, the demand-based transfer price indications in the FIT scenarios exceeds the supply-based price predominantly until 2014/2015, before the demand-based price drops to zero owing to an increasing surplus of electricity generation. Observing the development of the supply-based price indicator in the Policy_FIT_Dynamic Scenario, it becomes clear that prices increase in phases of a rapid diffusion of RET from 2018 – 2022. The price indicator estimated based on expectations from potential exporting countries shows a moderate development in both FIT scenarios and ranges between 10 €/MWh and 45 €/MWh.

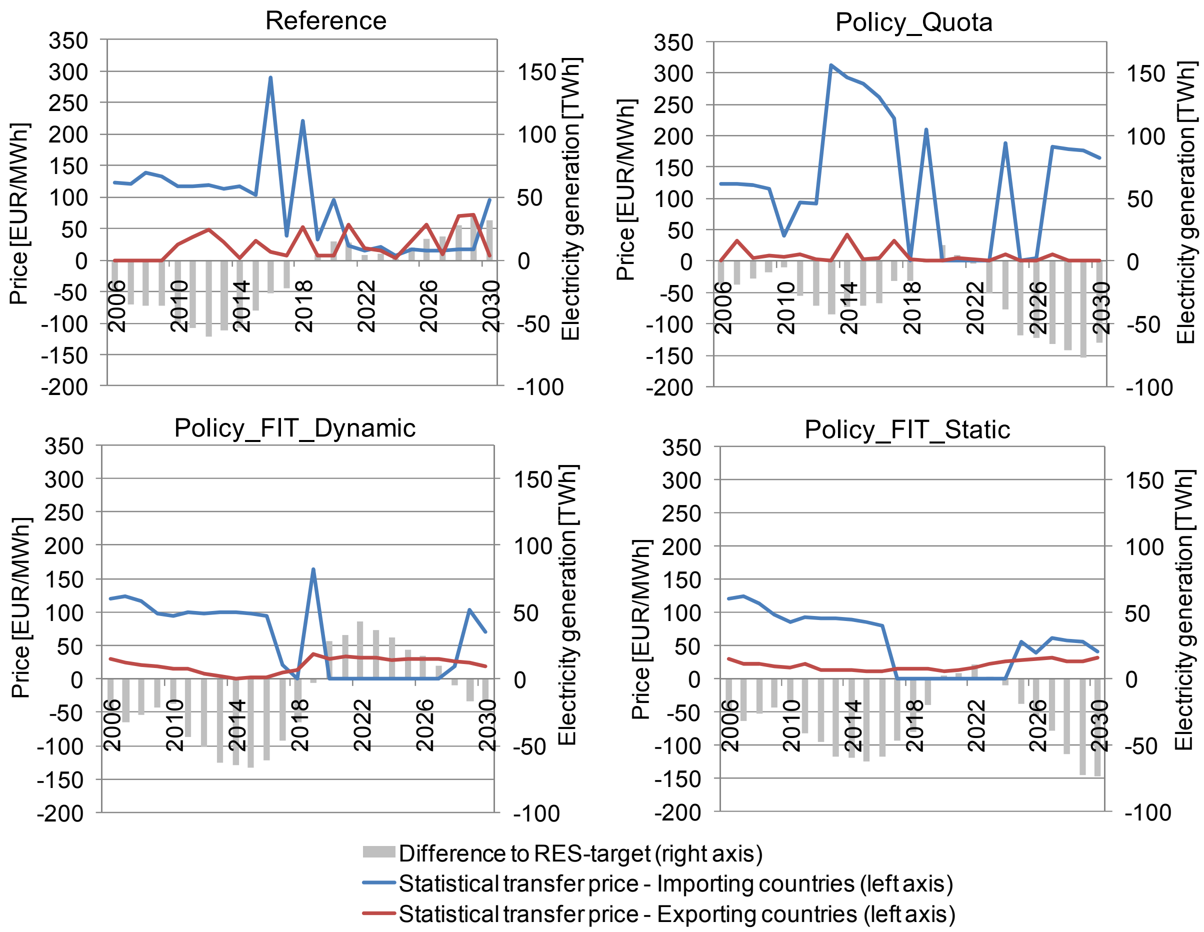

Figure 6-15 Price indication for statistical transfers and difference to RES-E target in all four scenarios from 2006 to 2030

Source: Own illustration based on scenario runs with PowerACE-ResInvest

Figure 6-16 shows the development of the policy costs corresponding to the difference between the total support paid for one unit of renewable electricity and the reference electricity price. Policy costs are depicted per unit of electricity produced in renewable power plants that have been installed additionally in the respective year. Owing to a high share of solar PV power plants in the additionally installed RET capacity mix and constant FIT remaining at a high level, policy costs in the Policy_FIT_Static Scenario rise up to 207 €/MWh in 2046. Hence, policy costs in this scenario clearly exceed those of the other scenarios during the last 20 years of the modelling period. Policy costs in both quota obligation scenarios are on a similar level. Thereby, the support cost development under Reference Scenario conditions is characterised by stronger fluctuations than under Policy_Quota conditions. In case of the Policy_FIT_Dynamic Scenario, policy costs increase until 2017 due to a strong RET development induced by an increase in FIT. After 2030 average policy costs show a decreasing trend as a result of the dynamic tariff design.

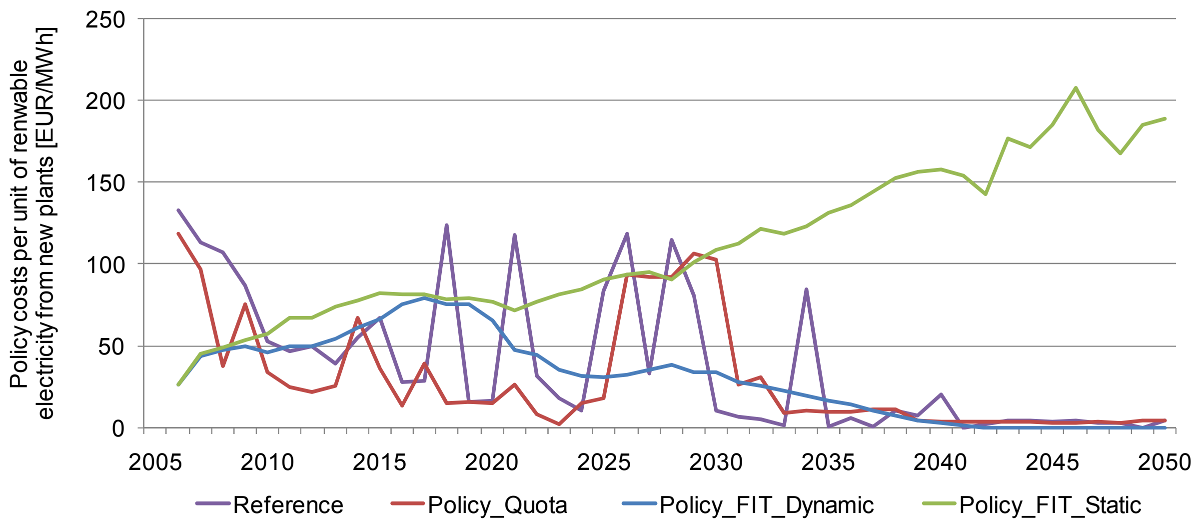

Figure 6-16 Average policy costs per unit of electricity generated by all renewable power plants built-up in the respective year

Source: Own illustration based on scenario runs with PowerACE-ResInvest

Besides the short-term averages of policy costs shown in Figure 6-16, it is of interest to look also on the long-term averages. Thus, Figure 6-17 depicts policy costs averaged by the cumulated electricity generation of all plants that have been built between the base year of the model and the respective simulation year. In both scenarios, where renewable electricity is promoted with a quota obligation, policy costs start at a comparatively high level – 133 €/MWh in the Reference Scenario and 119 €/MWh in the Policy_Quota Scenario – and show then a decreasing trend almost during the overall modelling horizon. In contrast, policy costs in the Policy_FIT_Static Scenario, starting at a moderate level of 26 €/MWh, shows an increasing trend and exceeds 100 €/MWh by 2050. In contrast, policy support costs in the Policy_FIT_Dynamic Scenario rise until 2020 and decrease afterwards. Policy costs averaged over cumulated renewable electricity generation between 2005 and 2050 are nearly the same in the Reference (47 €/MWh), the Policy_Quota (42 €/MWh) and the Policy_FIT_Dynamic Scenario (40 €/MWh).

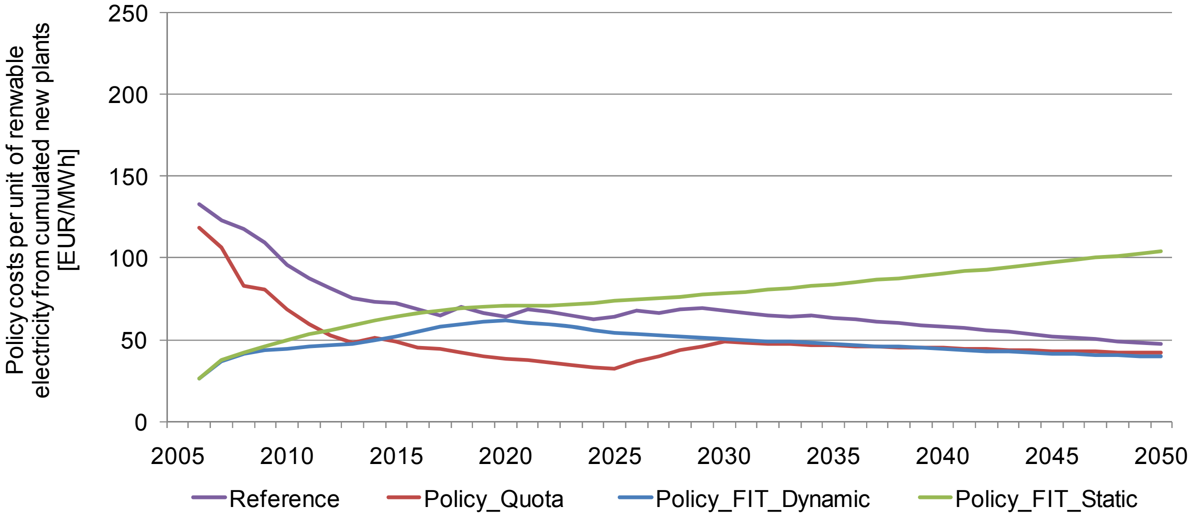

Figure 6-17 Average policy costs per unit of electricity generated by cumulated renewable power plants, built-up until the respective year

Source: Own illustration based on scenario runs with PowerACE-ResInvest

6.4 Impacts of climate change on hydropower generation

The hydrological impact of climate change is expected to affect the availability of water required by hydropower plants in order to produce electricity. These changes in water availability may have an impact on the economics of hydropower production and therewith influence investment decisions in new hydropower capacity. Owing to the exploitation of a large portion of the total hydropower potential already today, the overall hydropower capacity remains almost unaffected by climate change impacts.

Looking at the capacity that is built up during the modelling horizon, it can be observed that climate change appears to reduce the additionally installed capacity moderately by 2 % on EU-level until 2050 (see Table 6-4). However, Table 6-4 shows larger differences on regional level. In Western and Eastern European countries as well as in the Baltic States the increase in hydropower capacity between 2005 and 2040 is reduced by more than 10 % if climate change impacts are considered for the modelling runs. In contrast, Scandinavian countries appear to install roughly 10 % more hydropower capacity compared to the Reference Scenario as a result of hydrological impacts.

Table 6-4 Changes in cumulated capacity built up of hydropower plants as a consequence of climate change against the Reference Scenario.

Year	Western European countries	Eastern European countries	Southern European countries	Scandinavia	Baltic States	EU27
2010	0%	3%	3%	-7%	-9%	2%
2020	-8%	-8%	0%	-7%	-15%	-3%
2030	-11%	-5%	-3%	6%	-12%	-5%
2040	-13%	-10%	-2%	9%	-16%	-5%
2050	-6%	2%	-2%	9%	-15%	-2%

Source: Own illustration based on scenario runs with PowerACE-ResInvest

Compared to the moderate changes of hydropower capacity, model results suggest that hydropower production decreases by about 9 % at the EU level compared to the Reference Scenario (see Figure 6-18). Observing the development at regional level, one can see that some regions experience considerable changes in hydro electricity production. Whilst hydropower production in Northern European countries seems to augment, decreasing rainfall leads to reduced hydro electricity output in Southern and Eastern European countries. In Scandinavian and Baltic countries the hydropower production is expected to increase by approximately 10 % to 2050. By contrast, Southern and Eastern European countries may face a reduction in the electricity output of hydropower plants amounting to roughly 20 %. In general, one should take into account the uncertainty of the presented results given still little understanding of projecting changed river flows.

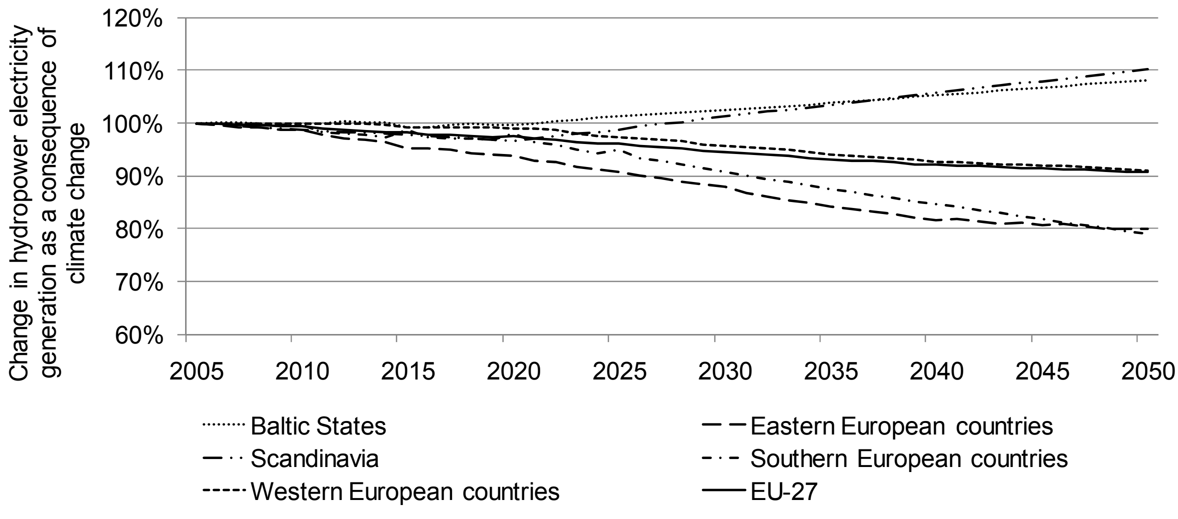

Figure 6-18 Changes in electricity generation of hydropower plants as a consequence of climate change against the Reference Scenario.

Source: Own illustration based on scenario runs with PowerACE-ResInvest

6.5 Sensitivity analysis

The diffusion of RET in the European electricity sector depends on the influence of various driving factors. To put some examples, these factors include the resource availability, the techno-economic characteristics of the respective conversion technologies, the individual profitability assessment of potential renewable energy projects, future cost development of RET and political framework conditions. Due to the high number of crucial input parameters the sensitivity analysis is realised exemplarily in order to consider changes in the resource availability and in the individual profitability assessment. Given the significant role of wind power in all scenarios, the impact of a hypothetical variation in the total wind power potential by 20 % is analysed. For the variation of the potential its breakdown to different cost levels remains the same as in the original potential.

In order to examine the consequences of individual profitability assessments, investment planner agents are supposed to use all the same interest rate of either 8 % or 12 %, reflecting a lower and an upper limit for the profitability calculations. Sensitivities are exemplarily illustrated for two scenarios, namely the Reference Scenario and the Policy_FIT_Dynamic Scenario. These two scenarios are selected in order to evaluate sensitivities of a moderate and a more ambitious RET development scenario. In addition, the Reference Scenario is characterised by the application of quota obligation whilst the Policy_FIT_Dynamic Scenario assumes the implementation of FIT systems.

Table 6-5 shows the impacts of a modified wind power potential on RES-E generation and on average policy costs in the Reference Scenario. Since average policy costs of the annually installed capacity fluctuate considerably from year to year, long-term averages of policy costs considering cumulative additional RET installations are taken as variable. Modelling results are characterised by a low sensitivity towards changes in resource availability. It becomes clear, that a change in the wind power potential by 20 % affects only moderately total RES-E generation and average policy costs of the cumulated installed RET capacity. In particular an increase in the wind power potential by 20 % compared to Reference Scenario conditions does not imply any changes for the total amount of RES-E generation to 2050.

A reduction of the wind power potential by 20 % implies that total RES-E generation in 2050 is 3 % lower than under Reference Scenario conditions. The associated decrease of electricity generation in wind power plants by 7 % against the Reference Scenario is partially substituted with additional electricity generated in biomass-based renewable power plants. The low sensitivity in a scenario characterised by a moderate diffusion of RET can be explained by the fact that the wind power potential is still far from being exploited to a large extent.

Table 6-5 Impact of wind energy potential variation on RES-E generation and average cumulated policy costs in the Reference Scenario

Year	**Impact of wind potential variation on RES-E generation**			**Impact of wind potential variations on average policy costs (cumulated)**		
	Reference Scenario	**Low** (Pot: 80%)	**High** (Pot: 120%)	**Reference Scenario**	**Low** (Pot: 80%)	**High** (Pot: 120%)
	RES-E generation [TWh]	Relative change [%]	Relative change [%]	Average policy costs [€/MWh]	Relative change [%]	Relative change [%]
2010	594	0%	0%	96	-6%	0%
2020	840	0%	0%	64	9%	9%
2030	1,093	0%	0%	68	2%	1%
2040	1,240	-1%	0%	58	2%	-5%
2050	1,422	-3%	0%	47	5%	-4%

Source: Own illustration based on scenario runs with PowerACE-ResInvest

In contrast, total RES-E generation and average policy costs of cumulated additionally installed capacity appear to be more sensitive towards changes in the interest rate (see Table 6-6). Assuming a homogeneous interest rate of 8 % total RES-E generation by 2050 is increased by 6 % compared to the RES-E development in the Reference Scenario. The impact of an interest rate changed to 12 % involves a relative decrease of RES-E generation by 6 % against the Reference Scenario by 2050. The given changes in the interest rate lead to a decrease of average cumulated policy costs by 30 % and to a rise by 28 % respectively.

Table 6-6 Impact of interest rate variation on RES-E generation and average cumulated policy costs in the Reference Scenario

Year	**Impact of interest rate variation on RES-E generation**			**Impact of interest rate variations on average cumulated policy costs**		
	Reference Scenario	**Low** (IR = 8%)	**High** (IR = 12%)	**Reference Scenario**	**Low** (IR = 8%)	**High** (IR = 12%)
	RES-E generation [TWh]	Relative change [%]	Relative change [%]	Average policy costs [€/MWh]	Relative change [%]	Relative change [%]
2010	594	2%	1%	96	-30%	+12%
2020	840	3%	-1%	64	-29%	+30%
2030	1,093	4%	-1%	68	-26%	+25%
2040	1,240	9%	-5%	58	-32%	+27%
2050	1,422	6%	-6%	47	-28%	+30%

Source: Own illustration based on scenario runs with PowerACE-ResInvest

Next, the impact of changes in the wind energy potential on RES-E generation and average policy costs are investigated for the case of the Policy_FIT_Dynamic Scenario, as shown in Table 6-7. On the one hand, the repercussions of wind potential variations on total RES-E generation are still moderate, amounting to a decrease of 2 % in the low wind potential case and to an increase of 1 % in the high potential scenario variant. The stronger change in the electricity output from wind power plants – amounting to -5 % by 2050 in case of a lowered potential and to +5 % in the high potential case – is partly substituted with electricity from other RET. On the other hand the impacts on average policy costs are considerably stronger than in case of variations in the Reference Scenario, increasing by 25 % in 2050 assuming only 80 % of the wind energy potential to be available and decreasing by 14 % as a result of increased wind resource availability. Missing wind energy potential is substituted either with wind energy potential steps characterised by higher electricity generation costs or with other RET. Comparing the sensitivity of a more ambitious scenario regarding the future development of RET (see Table 6-7) with the sensitivity in a scenario assuming a moderate diffusion of RET (see Table 6-5), it becomes clear that average policy costs become more sensitive with an increasing share of potential exploitation.

Table 6-7 Impact of wind energy potential variation on RES-E generation and average cumulated policy costs in the Policy_FIT_Dynamic Scenario

	Impact of wind potential variation on RES-E generation			**Impact of wind potential variations on average cumulated policy costs**		
	Policy_FIT_Dynamic Scenario	**Low** (Pot: 80%)	**High** (Pot: 120%)	**Policy_FIT_Dynamic Scenario**	**Low** (Pot: 80%)	**High** (Pot: 120%)
Year	RES-E generation [TWh]	Relative change [%]	Relative change [%]	Average policy costs [€/MWh]	Relative change [%]	Relative change [%]
2010	612	-2%	1%	45	4%	-1%
2020	1,061	-3%	2%	62	16%	-8%
2030	1,527	-2%	0%	50	21%	-12%
2040	1,757	-2%	1%	44	26%	-12%
2050	1,906	-2%	1%	40	25%	-14%

Source: Own illustration based on scenario runs with PowerACE-ResInvest

Finally, the sensitivity of RES-E generation and policy costs to changes in the interest rate is analysed for the Policy_FIT_Dynamic Scenario. Results depicted in Table 6-8 indicate that the impact of the interest rate on total RES-E generation is slightly lower than in the Reference Scenario. Given the assumption of imperfect TGC markets in the Reference Scenario and the dynamic nature of the FIT in the Policy_FIT_Dynamic Scenario, this difference is difficult to explain. In a situation assuming perfect TGC markets or the application of purely price-determined FIT, one would expect changes in the interest rate under a quantity-driven policy instrument such as a quota obligation to affect in particular policy costs and the RES-E development to a lesser extent. In contrast, a modification of the interest rate under the application of a price-driven policy instrument such as FIT suggests basically changes in the RES-E development and only minor impacts on the policy costs. However, this reasoning cannot be transferred to situations of imperfect TGC markets and the application of dynamic FIT which are no longer purely price-driven. The variety of additional factors and their combination influencing the development of RES-E generation and policy costs make it difficult to figure out the isolated impact of one factor. These factors include the level of electricity prices, the ambition level of the targets and the degree of target fulfilment.

Table 6-8 Impact of interest rate variation on RES-E generation and average cumulated policy costs in the Policy_FIT_Dynamic Scenario

Year	**Impact of interest rate variation on RES-E generation**			**Impact of interest rate variations on average cumulated policy costs**		
	Policy_FIT_Dynamic Scenario	**Low** (IR = 8%)	**High** (IR = 12%)	**Policy_FIT_Dynamic Scenario**	**Low** (IR = 8%)	**High** (IR = 12%)
	RES-E generation [TWh]	Relative change [%]	Relative change [%]	Average policy costs [€/MWh]	Relative change [%]	Relative change [%]
2010	612	4%	-2%	45	-9%	7%
2020	1,061	4%	-2%	62	-30%	15%
2030	1,527	1%	-1%	50	-35%	36%
2040	1,757	2%	0%	44	-35%	42%
2050	1,906	1%	-1%	40	-39%	43%

Source: Own illustration based on scenario runs with PowerACE-ResInvest

7 Conclusions and Outlook

Since substituting fossil-fuel based electricity supply with renewable energy technologies (RET) serves to combat climate change, the European Union is planning to increase the share of RET in the EU's gross final energy consumption to 20 % by 2020 (The European Parliament and the Council of the European Union 2009a). Several factors seriously influence the future prospects for the use of RET including the regionally varying combination of the available resource potential and the associated electricity generation costs, referred to as cost-resource curves. Member States (MS) have been applying several support measures such as feed-in tariffs or quota obligations to compensate for the prevailing higher conversion costs of RET compared to those of conventional technologies. Thus, an active debate about appropriate policy design has been encouraged throughout the EU. In this context, the question emerges as to how the use of RET will develop in the future under different policy regimes.

A quantitative modelling tool has been developed to answer this question. Since the diffusion of RET appears to be driven by the decentralised decision processes of potential investors (cf. Dinica 2006) the application of an agent-based simulation methodology was favoured over optimising approaches which tend to adopt the perspective of a central planner. The developed agent-based modelling approach allows, for the first time the future development of RET to be assessed, taking into account the individual actor's perspective as well as the geographically explicit availability of RES and conversion costs.

Subsequently, the suitability of the developed approach is discussed focussing first on the derivation of the geographically explicit cost-resource curves and then on the developed multi-agent based simulation model. After this, conclusions are drawn with regard to the long-term evolution of RET in the European electricity sector. The chapter closes with an outlook of how the developed approach could be extended and improved in future research.

7.1 Conclusion on cost-resource curves for renewable energy sources

Owing to the key role of the available resource potential and energy conversion costs for the future prospects of RET detailed cost-resource curves have been derived for a large variety of technologies. Whilst the current literature was reviewed to provide cost-resource curves for most of the available RET, a more detailed analysis was done for onshore wind and solar PV power plants for the following reason: Due to the strong spatial dependence of the potential and the costs of wind and solar power a geographical information system (GIS) was applied in order to take into account the geographical characteristics of both technologies.

Three main factors mainly determine the cost-resource curves of both wind and solar energy. The first factor is the regionally heterogeneous meteorological regime with its strong influence on the potential energy yield of the renewable power plant. The second is the land area available for the construction of the renewable power plant which restricts the total available potential in terms of the installed electric capacity. The third factor comprises the economic characteristics of the respective conversion technologies such as specific investments as well as operation and maintenance costs which considerably affect the cost-resource curves. These factors are derived and combined to create the final cost-resource curves for solar PV and onshore wind energy.

Looking at the case of onshore wind energy, the land area available for the construction of wind turbines was estimated by excluding unsuitable areas and subsequently combined with the full-load hours of a turbine resulting from information on the wind regime. Thereby, the full-load hours describe the ratio between the electricity output of a wind turbine and its rated capacity. With regard to the cost-resource curves for solar PV power plants, the spatial distribution of the irradiation-based data was used to split up the estimated capacity potential at national level into different categories of utilisation instead of directly overlapping both types of maps.

Some simplifying assumptions were made to meet the challenges resulting from the broad geographical scope and a high spatial resolution. With regard to the wind energy potential wind speed data available for an altitude of 10 m were corrected to a typical hub height without considering potential differences in atmospheric weather conditions. Similarly, the effects of temperature on the efficiency of solar PV modules have been neglected. Finally, it should be noted that wind and solar energy potentials are highly sensitive to the area availability and the applied weather-related data such as wind speed and solar irradiation. Annual averages of wind speed and solar irradiation values were applied for the analysis to keep processed data to a manageable level. Given the wide geographical scope and the time horizon, the above mentioned limitations appear to be acceptable considering that the overall intention is to estimate the magnitude of available renewable energy potential for the EU as a whole and the corresponding electricity generation costs.

7.2 Conclusion on the agent-based simulation model

An agent-based simulation model has been developed to map investment decisions for RET in the EU power sector in this thesis. The future market development of RET is judged to depend in particular on individual investor's decisions (cf. Dinica 2006). A heterogeneous agent structure has been constructed in the model to reflect the diverse investment strategies of investors to take into account the investors' perspective.

Besides the investment planner agents, the model also includes government agents who determine the design of the policy instruments to support RET. One selected government agent is equipped with the ability to dynamically adapt support conditions to certain developments of the environment. The model in its current version is able to represent currently used policy schemes including feed-in tariff systems and quota obligations applied in combination with tradable green certificates. In view of analysing several policy options, the model developed in this thesis is the first one to feature the analysis of price formation procedures for the statistical transfer of renewable final energy between countries.

The multi-actor structure of the model is required to extend the concept of the cost-resource curves. Assuming that the investors' have varying economic evaluations of one investment opportunity for RET, one potential step is no longer characterised unambiguously by identical economic indicators, but rather by a set of economic indicators depending on the investment strategies of the agents. To account for the dynamic development of conversion costs over time, the impacts of technological learning have been integrated into the model.

Due to the comprehensive consideration of the relevant technical, political and economic framework conditions European and national policy decision-makers can use the developed modelling tool for decision support. Thus, the model may help to shape the concrete design of policy instruments applied to support RET such as determining the financial support level for feed-in tariffs. The price indications for statistical transfers may help Member States to decide on which strategy to pursue to meet their targets; either relying exclusively on the domestic exploitation of renewable energy sources, or supplementing indigenous renewable energy supply with statistical imports. However, it should be mentioned that the application of the model in its current version is restricted to the evaluation of RET in the power sector and is not able to analyse interdependencies with the development of RET use in the heat and in the transport sectors. The simulation model can be used to point out existing investment opportunities for interested stakeholders and indications about the future market potential of RET on a technology level.

The main difficulty in developing the presented agent-based simulation model to map the future development of RET in the power sector is related to the quantification of the agents' characteristics. Due to missing data availability on the crucial characteristics of commercial actors such as capital availability and investment strategies, the investment agents' design and classification could not be empirically supported. Instead, the aim was to describe the agents based on parameters which were judged to reflect real conditions as much as possible.

7.3 Conclusion on the prospects of renewable energies in the EU's electricity sector

If adequate support instruments are applied, scenario results indicate that a strong future market development of RET appears to be feasible. Depending on the degree of political ambition and the type of policy instrument applied, electricity generation from RES is expected to reach between 1.4 and 2.0 PWh by 2050. This development involves total investments ranging from 791 billion euro to 1,273 billion euro in the period from 2005 to 2050. In particular onshore wind power plants are expected to experience considerable growth rates as a result of the significant resource potential and the low electricity generation costs compared to other RET alternatives.

Looking at the investment planner agents responsible for the investments made in the renewable energy sector, the model analysis revealed that agent behaviour affects investments in renewable power plants. The agent-specific evaluation of the project profitability and varying preferences for certain RET imply that less innovation-oriented agents invest to a lesser extent in renewable energy capacity than investment planner agents who tend to be earlier in adopting new concepts and ideas. Even though the investment planner agents 'Early Majority' and 'Late Majority' have the same amount of capital available, the 'Early Majority' invests more than twice as much in renewable energy projects as the ‘Late Majority’ in all scenarios considered.

Comparing the results of modelling different support mechanisms reveals that the additional renewable power plant capacity being built fluctuates more strongly when quota obligations are applied. This is essentially due to the high sensitivity of the certificate prices to the quota targets. As a result only slight increases in the target may require the deployment of a technology with considerably higher electricity generation costs if cheaper technologies are no longer available for the respective time slice of one year. Since the certificate price is calculated on an annual basis, potential price adjustments over the course of the year are disregarded in the model, e.g. if the target has been achieved, As a result, targets are not necessarily exactly met. In contrast, the capacity growth induced by feed-in tariffs appears to be steadier. Scenario runs indicate that quota obligations are better suited to meet predetermined targets, but are rather sensitive to price fluctuations.

Another conclusion drawn by this study is that technology-specific policy support tends to imply lower policy costs than technology-neutral support. In this context, ‘policy costs‘ refer to the average price paid for one unit of renewable electricity on top of the average electricity price. Although RES-E development under the application of quota obligations and ambitious renewables targets is lower than in a comparable scenario where dynamic feed-in tariffs are used, the average policy costs of all additionally installed renewable power plants is more or less the same in both scenarios. Observing the respective technology mix, it should be noted that the amount of cost-intensive solar electricity achieved under feed-in tariff conditions exceeds that of the quota obligation scenario by a factor of seven, even though average policy costs until 2050 are almost identical. However, if feed-in tariffs are assumed to remain at a constant level, average policy costs are considerably higher, amounting to 104 €/MWh for the renewable capacity constructed between 2005 and 2050. In comparison, the average support costs under a quota obligation or dynamic feed-in tariffs are just over 40 €/MWh. This means that the dynamic tariff design of responsive national governments contributes considerably to reducing policy costs.

Looking at the new option proposed by the European Commission to exchange renewable electricity produced abroad for target accounting in terms of statistical transfers, the question arises about which prices evolve if such an international trading mechanism is established. This includes the price expectations of countries disposing of surplus electricity as well as the prices resulting from the willingness-to-pay of potential importers. Modelling results have shown that price indications for statistical transfers heavily depend on the difference between renewable targets and actual electricity generation at national level. The statistical transfer prices potential importing countries are willing to pay tend to be considerably higher than the price level demanded by potential exporting countries in periods when targets are not being achieved. The reason for this is that exporting countries possess relatively abundant low-cost potentials beyond their own target achievement. In contrast, demand-based price indications tend to decrease or even drop to zero if more electricity is generated than required by the predetermined targets. According to the modelling results, transfer price indications resulting from the expectations of potential exporters show a comparatively smooth course over time, whilst demand-based prices are characterised by higher fluctuations. In addition, both price indications tend to fluctuate more strongly if renewables are supported by quota obligations than is the case with feed-in tariffs.

7.4 Outlook

The modelling approach developed to investigate the long-term prospects of renewable energy technologies in the European power sector could be extended to address additional research questions.

This model with its focus on the renewable sector could be linked to an electricity market model with a higher temporal resolution to consider the partially fluctuating character of renewable electricity generation and the associated impacts for the operation of the electricity system. This would also allow the impacts of different renewable support schemes on the overall electricity market to be analysed. According to the modelling analysis, the future mix of RET depends on the type of support instrument implemented. As a consequence, the ability of the electricity market to integrate fluctuating RES-E can vary depending on the dispatchability of the electricity produced by different RET.

One aspect needing to be addressed is the question whether each support instrument analysed tends to favour a certain type of investor or a certain size of RET projects. Market-based renewable support mechanisms such as quota obligations, which are usually characterised by higher price risks and larger project sizes, may be inclined to attract investors able to handle these risks such as large utilities or other financially sound investors. In contrast, price-based mechanisms such as feed-in tariffs typically provide sufficient investment security for smaller investors as well. The potentially differing investor structure under each support scheme may lead to different market behaviour and thus influence the functioning of the electricity market. In addition, market-based support schemes may be more effective than price-based mechanisms in encouraging the operators of renewable power plants to participate in the electricity market.

Another option for future research is related to the empirical foundation of agent behaviour. To improve the knowledge basis on the structure and motivation of the investment planner agents, in particular, it is suggested to conduct interviews or questionnaire-based surveys. The calibration of other model parameters could also be supported by such surveys, including, e.g. the share of projects that are authorised. The obvious drawback her is that the broad geographical coverage would presumably involve significant data collection efforts. In principle, it is possible to provide agents with the capability to learn from their decisions. In this context, it should be considered that the choice of the learning algorithm may substantially influence the results.

With regard to the representation of support policies, the design of the policy instruments analysed with the model can be refined, e.g. by introducing a technology-specific quota obligation or representing additional instruments such as tax incentives or investment subsidies. The simulation model could also be extended by representing the strategic behaviour of government agents with respect to fulfilling renewable targets mainly domestically or additionally supported by statistical imports of renewable energy. In this way, one could reflect the fact that governments may prefer the domestic use of renewable energy sources even if the statistical import of renewable energy promises to be more cost efficient.

Given that renewable targets are determined for the final energy supplied in the electricity, heat and transport sector, the scope of the model could be extended to heating and cooling as well as the transport sector. This would enable a comprehensive evaluation of the development and monitoring of Member States' target compliance as, e.g. required by the 'National Renewable Energy Action Plans', which had to be delivered by the end of June 2010. Similarly, the analysis of issues concerning the statistical transfers of renewable energy could be improved by taking into account potential compensation between the final energy sectors. Moreover, potential interdependencies of statistical transfer prices and the national support instruments such as feed-in tariffs or quota obligations could be investigated. Further research is required here given the complex conditions governing price formation and the fact that many other design issues of statistical transfers are still outstanding including those regarding the balancing of costs and benefits.

In general, the flexible design of the developed simulation model PowerACE-ResInvest facilitates the implementation of potential extensions to the model and provides an adequate quantitative tool for future research.

8 Deutsche Zusammenfassung

Bedingt durch die geringen Treibhausgasemissionen, die mit der Nutzung erneuerbare Energiequellen verbunden sind, stellt die Erhöhung des Anteils erneuerbarer Energiequellen an der Endenergiebereitstellung auf 20 % bis zum Jahr 2020 ein wichtiges strategisches Ziel europäischer Energie- und Klimapolitik dar. Für die zukünftige Diffusion von erneuerbaren Energietechnologien sind insbesondere deren geografische Verfügbarkeit sowie die entsprechenden Kosten zur Nutzenergiebereitstellung, die derzeit überwiegend über den Kosten konventioneller Umwandlungstechnologien liegen, ausschlaggebend. Um die wirtschaftliche Konkurrenzfähigkeit dieser Technologien auf den Energiemärkten herzustellen, werden seit mehr als zehn Jahren diverse Fördermechanismen eingesetzt. Vor diesem Hintergrund stellt sich die Frage wie sich die Nutzung erneuerbarer Energiequellen insbesondere im Stromsektor langfristig unter dem Einsatz verschiedener Politikinstrumente entwickeln wird und welche ökonomischen Auswirkungen damit verbunden sind.

Zur Bearbeitung dieser Fragestellung wurde im Rahmen dieser Dissertation ein quantitatives Modellinstrumentarium entwickelt. Da die zukünftige Marktentwicklung von Technologien zur Nutzung erneuerbarer Energieträger insbesondere von individuellen Investitionsentscheidungen abhängt, fiel die Entscheidung zugunsten des Ansatzes der agentenbasierten Simulation, der globale Zusammenhänge basierend auf Interaktionen auf der Mikroebene beschreibt. Um die techno-ökonomischen Eigenschaften erneuerbarer Energietechnologien und die geografische Dimension der Energieträgerverfügbarkeit zu berücksichtigen, wurden eigene Kostenpotenzialkurven abgeleitet und in das Simulationsmodell integriert. Das entwickelte Modell kann zur konkreten Ausgestaltung von Politiken wie beispielsweise der Tarifgestaltung im Fall von Einspeisesystemen eingesetzt werden oder Investitionsmöglichkeiten für interessierte Stakeholder aufzeigen. Auch für die neu vorgeschlagene Politikoption, statische Transfers von Nutzenergie zwischen Ländern als Beitrag zur nationalen Zielerfüllung zu ermöglichen, gibt das Modell Aufschluss, über mögliche Transferpreise.

Werden geeignete Politikinstrumente zur Förderung erneuerbarer Energien eingesetzt, erscheint entsprechend der Szenarienergebnisse ein starkes Marktwachstum erneuerbarer Energietechnologien im europäischen Stromsektor realisierbar. In Abhängigkeit der hinterlegten politischen Zielsetzungen und der eingesetzten Förderinstrumente, können bis 2050 zwischen 1,4 und 2,0 PWh Strom basierend auf erneuerbaren Technologien erzeugt werden. Dieser Ausbau wäre mit Gesamtinvestitionen in der Größenordnung von 791 Milliarden bis 1,273 Billionen Euro im Zeitraum von 2005 bis 2050 verbunden. Insbesondere Windkraftanlagen (Onshore) sind in den Modellrechnungen bedingt durch ein erhebliches Potenzial und vergleichsweise geringer Stromgestehungskosten von einem beträchtlichen Kapazitätszubau gekennzeichnet. Ein Vergleich der Anwendung verschiedener Politikinstrumente zeigt, dass der jährliche Kapazitätszubau beim Einsatz von Quotenregelungen deutlich stärker fluktuiert als im Fall von Einspeisesystemen. Dies liegt in der hohen Sensitivität der Zertifikatspreise in Bezug auf die Quotenziele begründet. Letztendlich lassen die Modellergebnisse vermuten, dass technologiespezifische Förderung tendenziell zu niedrigeren Förderkosten führt als eine technologieunabhängige Förderung.

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Annex

Table A-1 National targets for the share of renewables in gross final energy consumption

	Share of renewables in gross final energy consumption 2005	Target for share of renewables in gross energy consumption in 2020
Austria	23.3%	34%
Belgium	2.2%	13%
Bulgaria	9.4%	16%
Cyprus	2.9%	13%
Czech Republic	6.1%	13%
Denmark	17%	30%
Estonia	18%	25%
Finland	28.5%	38%
France	10.3%	23%
Germany	5.8%	18%
Greece	6.9%	18%
Hungary	4.3%	13%
Ireland	3.1%	16%
Italy	5.2%	17%
Latvia	32.6%	40%
Lithuania	15%	23%
Luxembourg	0.9%	11%
Malta	0%	10%
The Netherlands	2.4%	14%
Poland	7.2%	15%
Portugal	20.5%	31%
Romania	17.8%	24%
Slovak Republic	6.7%	14%
Slovenia	16%	25%
Spain	8.7%	20%
Sweden	39.8%	49%
United Kingdom	1.3%	15%

Source: (The European Parliament and the Council of the European Union 2009a)

Table A-2 Assumed suitability factors per land use category

Level 1	Level 2	Level 3	Suitability
1. Artificial surfaces	1.1. Urban fabric	1.1.1. Continuous urban fabric	0
		1.1.2. Discontinuous urban fabric	0
	1.2. Industrial, commercial and transport units	1.2.1. Industrial or commercial units	0
		1.2.2. Road and rail networks and associated land	0
		1.2.3. Port areas	0
		1.2.4. Airports	0
	1.3. Mine, dump and construction sites	1.3.1. Mineral extraction sites	0
		1.3.2. Dump sites	0
		1.3.3. Construction sites	0
	1.4. Artificial non-agricultural vegetated areas	1.4.1. Green urban areas	0
		1.4.2. Sport and leisure facilities	0
2. Agricultural areas	2.1.Arable land	2.1.1. Non-irrigated arable land	0.35
		2.1.2. Permanently irrigated land	0.35
		2.1.3. Rice fields	0.35
	2.2. Permanent crops	2.2.1. Vineyards	0.1
		2.2.2. Fruit trees and berry plantations	0.1
		2.2.3. Olive groves	0.1
	2.3. Pastures	2.3.1. Pastures	0.35
	2.4. Heterogeneous agricultural areas	2.4.1. Annual crops associated with permanent crops	0.1
		2.4.2. Complex cultivation	0.1
		2.4.3. Land principally occupied by agriculture, with significant areas of natural vegetation	0.1
		2.4.4. Agro-forestry areas	0.1
3. Forests and semi-natural areas	3.1. Forests	3.1.1. Broad-leaved forest	0.1
		3.1.2. Coniferous forest	0.1
		3.1.3. Mixed forest	0.1
	3.2. Shrub and/or herbaceous vegetation association	3.2.1. Natural grassland	0.5
		3.2.2. Moors and heathland	0.5
		3.2.3. Sclerophyllous vegetation	0.5
		3.2.4. Transitional woodland shrub	0.5
	3.3. Open spaces with little or no vegetation	3.3.1. Beaches, dunes, and sand plains	0.1
		3.3.2. Bare rock	0
		3.3.3. Sparsely vegetated areas	0.8
		3.3.4. Burnt areas	0
		3.3.5. Glaciers and perpetual snow	0
4. Wetlands	4.1. inland wetlands	4.1.1. Inland marshes	0.1
		4.1.2. Peat bogs	0.1
	4.2. Coastal wetlands	4.2.1. Salt marshes	0.1
		4.2.2. Salines	0.1
		4.2.3. Intertidal flats	0.1
5. Water bodies			0

Source: Land use categories taken from CORINE land cover 2000