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ASSESSMENT OF THE EUROPEAN ENERGY CONVERSION SECTOR UNDER CLIMATE CHANGE SCENARIOS

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ULRICH REITER

Dipl. Umwelt-Ing. ETH
born 23rd of September 1976
citizen of Zurich, Switzerland and Germany

accepted on the recommendation of

Prof. Dr. A. Wokaun, examiner
Prof. Dr. R. Knutti, co-examiner
Dr. H. Turton, co-examiner

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Nomenclature / Abbreviations

$^{\circ}$C	Degree Celsius
ADAM	ADaptation And Mitigation, European Project
CCS	Carbon Capture and Sequestration
CH_4	Methane
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CO_2-eq	Carbon Dioxide Equivalent
COP-15	15th Conference of the Parties to the UNFCCC
Cum.	Cumulative
DC	Dry Cooling Technologies
EJ	Exa-joules
ENTSOE	European Network of Transmission System Operators for Electricity
EU	European Union
EU27+2	27 Member States of the European Union, plus Norway and Switzerland
EuroMM	European Multi-regional MARKAL model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GHGE	Greenhouse Gas Emissions
GIS	Geographic Information System
GMM	Global MARKAL Model
Gt	Giga-tons
GTCC	Gas Turbine Combined Cycle
GW	Giga-watt
H_2	Hydrogen
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
Inv.	Investment(s)

IPCC	Intergovernmental Panel on Climate Change
km	Kilometer(s)
LPG	Liquefied Petrol Gas
LTH	Low Temperature Heat
LULUCF	Land Use and Land Use Change or Forestry
m^3	Cubic Meters
M$	Million US-Dollar
MIP	Mixed Integer Programming
MIT1 to MIT0	Mitigation Scenarios, 450 ppm CO_2-eq
MITA to MITK	Mitigation Scenarios, 400 ppm CO_2-eq
Mm^3	Million Cubic Meters
Mt	Million Tonnes
MW	Mega-watt
N_2O	Nitrous Oxide
NGa	Natural Gas
NGCC	Natural Gas Combined Cycle
OTC	Once Through Cooling System
PJ	Peta-joules
POLES	Prospective Outlook on Long-term Energy Systems Model
PowerACE	Agent Based Simulation Model
ppm(v)	Parts Per Million (Volume)
PV	Photovoltaics
R^2	Coefficient of Determination
RES	Reference Energy System
RET	Renewable Energy Technologies
RF	Radiative Forcing
ROW	Rest of the World
SF_6	Sulfur Hexafluoride
SMM	Swiss MARKAL Model
SRAF	Seasonal Reservoir Availability Factor
TDSC	Total Discounted System Cost
TPES	Total Primary Energy Supply
TWh	Tera-watt-hour
UK	United Kingdom
UNFCCC	United Nation Framework Convention on Climate Change

Abstract

This dissertation deals with climate change adaptation and mitigation aspects which are of relevance for the European energy conversion sector in the future. The awareness of rising greenhouse gas emissions and related impacts has increased in the last years, leading to increasing concern from policy makers, decision makers and the public about the possible impacts, and outcomes of likely changes on various dimensions of the living environment. As one of the main sources for greenhouse gas emissions, the energy conversion sector is under special focus regarding greenhouse gas mitigation strategies. Especially electricity generation with mainly large point-sources for greenhouse gas emissions such as CO_2, provides important opportunities for reducing direct emissions from fossil fuel burning by means of fuel switching and carbon capture and sequestration, among others. However, climate change adaptation is also likely to become more important in the future for the energy conversion sector since climate change impacts such as rising temperatures, changing weather conditions, and weather extreme events will potentially influence the energy infrastructure.

In this dissertation, the European energy conversion sector and with special focus, the electricity generation sector were analyzed regarding the impacts of climate change on the energy infrastructure, and possible greenhouse gas emission reduction pathways, in respect of costs, and energy system parameters, such as technology choices and capacity installation. Therefore, a cost optimization model was built up and used to investigate a wide range of possible future scenarios, describing the development of the energy sector of 18 European regions, under a set of given assumptions. In this model, power generation technologies from small scale CO_2-free power generation units, to large scale conventional fossil power generation systems, an electricity transportation and distri-

bution system, as well as fuel production technologies for fossil fuels, biofuels and hydrogen were implemented based on cost, availability and efficiency parameters. All scenarios were analyzed for a time horizon until 2050.

Additionally, the model included special features on power plant availabilities, the use of water for cooling of thermal power capacity and incorporated estimates on river temperatures. The optimization model was solved as a mixed integer problem, to make lumpy capacity investments for large scale technologies available.

It was the aim of the dissertation to identify important measures needed in the energy sector, to prepare for a future under changed conditions. This has been achieved by presenting for a first time results on options for technology deployment, energy system development and cost-estimates for adapting the European energy conversion sector to climate change as well as presenting results for stringent mitigation scenarios, including analyses of different policy and technological uncertainties. In the scenario analysis of adaptation, it has been found that especially southern Europe needs to prepare for warmer climate. It has been found that expected higher water temperatures of rivers are likely to decrease availability and efficiency of thermal power plants, and that reduced river runoff is likely to decrease the output of hydro power in the future, under a warmer climate. To cope with such instances, costly investments in advanced cooling technologies are mandatory in southern Europe. Nordic European countries on the other hand may profit from warmer temperatures, decreasing the energy consumption for space heating, and an increased precipitation is likely to favor additional output of hydro power. However, in this study, the impacts of extreme and uncertain weather events based on climate change were not considered, potentially adding to the need for costly adaptation measures.

In the analysis of mitigation scenarios it was found that the European electricity sector can reduce greenhouse gas emissions by up to 90% until 2050, under stringent climate targets. However, large changes to the energy infrastructure are necessary to achieve such targets. Especially the deployment of CO_2-free technologies such as wind power and the extension of the electricity grid for trade purposes are mandatory to

reduce the costs of mitigating climate change. Furthermore, emissions reductions from other sectors are needed to ensure, stringent mitigation targets can be reached, allowing to stabilize climate change below 2 °C increase until 2100.

The results which are presented in this dissertation are highly relevant for policy makers and utilities which need to consider adaptation and mitigation measures in the design of future energy infrastructure. While clear policies regarding climate change mitigation targets support the deployment of new energy technologies, utilities need to mobilize the necessary investments to achieve such targets.

Keywords: Climate Change Adaptation and Mitigation; European Energy Conversion Sector; Model Analysis

Kurzfassung

Diese Dissertation behandelt Anpassungs- und Verminderungsaspekte des Klimawandels welche in Zukunft für den Europäischen Energie Sektor relevant sind. Die Erkenntnis über wachsende Treibhausgas Emissionen und deren Einflüsse hat in den letzten Jahren zugenommen und zu wachsenden Bedenken seitens Politikern, Entscheidungsträgern und der Bevölkerung geführt, bezüglich möglicher Einflüsse und Folgen wahrscheinlicher Klimaänderungen auf verschiedene Dimensionen der Umwelt. Als eine der Hauptquellen für Treibhausgase steht der Energiesektor unter spezieller Beobachtung bezüglich Emissions-Reduktions-Massnahmen. Insbesondere die Stromproduktion, mit meist grossen Punktquellen für Treibhausgas Emissionen wie CO_2, bietet wichtige Chancen, direkte Emissionen aus der Verbrennung von fossilen Brennstoffen durch den Ersatz solcher und durch CO_2-Abscheidung und -Lagerung zu reduzieren. Aber wahrscheinlich auch die Anpassung an den Klimawandel wird in Zukunft für den Energiesektor wichtiger, da die Folgen des Klimawandels wie z.B. steigende Temperaturen, ändernde Wetterbedingungen und -Extremvorkommnisse die Energie-Infrastruktur potenziell beeinflussen werden.

In dieser Dissertation wird der Europäische Energiesektor und insbesondere der Stromsektor bezüglich der Einflüsse des Klimawandels auf die Energie-Infrastruktur sowie mögliche Treibhausgas Reduktions-Pfade analysiert, hinsichtlich Kosten und Energiesystem-Parametern wie z.B. der Wahl von Energie-Technologien und Kraftwerks-Neubauten. Dazu wurde ein Kosten-Optimierungs-Modell erstellt und genutzt, um einen weiten Rahmen an möglichen, zukünftigen Szenarien zu untersuchen, welche die Entwicklung der Energiesektoren von 18 Europäischen Regionen unter bestimmten Voraussetzungen beschreiben. Im genannten Modell wurden kleine Einheiten von CO_2-freien -, sowie grosse Einhei-

ten von konventionellen fossilen Technologien zur Stromproduktion, ein Stromnetzwerk, Technologien zur Herstellung von fossilen und biologischen Treibstoffen sowie Wasserstoff eingeführt und anhand von Kosten, Verfügbarkeits- und Wirtschaftlichkeits-Parametern definiert. Alle untersuchten Szenarien wurden über den Zeithorizont bis 2050 analysiert.

Zusätzlich beschreibt das Modell Besonderheiten zu Verfügbarkeiten von Kraftwerken, zur Nutzung von Kühlwasser in thermischen Kraftwerken und es beinhaltet Abschätzungen zu Fluss-Temperaturen. Das Optimierungs-Modell wurde als gemischt-ganzzahliges Problem gelöst, um blockweise Kraftwerks-Investitionen für grosse Technologien zu ermöglichen.

Das Ziel dieser Dissertation war es, notwendige Massnahmen im Energiesektor zu identifizieren, um diesen auf eine Zukunft unter geänderten Rahmenbedingungen vorzubereiten. Dieses Ziel wurde erreicht, indem erstmalig Resultate präsentiert werden konnten zu Möglichkeiten der technischen Entwicklung, der Energie-System Entwicklung, zu Kostenfolgen auf Grund der Anpassung des Europäischen Energiesektors an den Klimawandel sowie Resultate präsentiert wurden zu bindenden Reduktions-Szenarien, welche verschiedene Analysen unterschiedlicher politischer und technischer Unsicherheiten beinhalten. In der Szenario-Analyse zur Anpassung an den Klimawandel konte gezeigt werden, dass sich insbesondere Südeuropa auf ein wärmeres Klima vorbereiten muss. Es wurde gezeigt, dass unter einem wärmeren Klima die erwarteten höheren Wassertemperaturen von Flüssen, voraussichtlich die Verfügbarkeit und Effizienz von thermischen Kraftwerken reduzieren und dass reduzierte Abflussmengen die Stromproduktion von Wasserkraftwerken in Zukunft verringern werden. Um mit solchen Umstände umgehen zu können werden teure Investitionen in fortschrittliche Kühltechnologien in Südeuropa notwendig sein. Nordeuropäische Länder können andererseits vielleicht von wärmeren Temperaturen profitieren, da sie den Energiebedarf zu Heizzwecken reduzieren und zusätzlich eine wahrscheinliche Zunahme der Niederschläge die Strommenge aus Wasserkraft erhöht. Jedoch wurden die Einflüsse von extremen und seltenen Wetterereignissen in dieser Arbeit nicht berücksichtigt, was voraussichtlich zu zusätzlichen teuren Anpassungs-Massnahmen beitragen wird.

In den Untersuchungen zu den Szenarien zur Verminderung des Kli-

mawandels konnte gezeigt werden, dass der Europäische Stromsektor bis zu 90% der Treibhausgas Emissionen bis 2050 reduzieren kann, bei bindenden Klima-Zielen. Jedoch werden grosse Veränderungen an der Energie-Infrastruktur notwendig, um diese Ziele zu erreichen. Insbesondere die Entwicklung von CO_2-freien Technologien zur Stromerzeugung wie z.B. Windturbinen und die Erweiterung des Stromnetzes zu Handelszwecken sind notwendig, um die Kosten zur Verminderung des Klimawandels zu reduzieren. Des Weiteren sind Emissions-Reduktionen von anderen Sektoren notwendig, um sicherzustellen, dass bindende Klima-Ziele erreicht werden können welche es erlauben, den Temperaturanstieg bis 2100 auf unter 2 °C zu begrenzen.

Die Resultate die in dieser Dissertation präsentiert werden sind von hoher Relevanz für Politiker und Energieunternehmen welche Anpassungs- und Verminderungsmassnahmen berücksichtigen müssen in der Gestaltung der zukünftigen Energie-Infrastruktur. Während klare politische Richtlinien bezüglich der Ziele zur Verminderung des Klimawandels die Entwicklung von neuen Technologien unterstützen, müssen Energieunternehmen die notwendigen Investitionen mobilisieren, um diese Ziele zu erreichen.

Stichwörter: Anpassung und Verminderung Klimawandel; Europäischer Energiesektor; MARKAL

1. Introduction

1.1. Motivation

A sustainable energy system integrates social, economic as well as environmental needs and targets. Based on todays knowledge, however, there is strong indication that the current energy system and current development trends of the system do not necessarily comply with these targets on global as well as on regional level. Since an important dimension of sustainability is related to climate change (Bernstein et al., 2007), special concern arises, induced by increasing anthropogenic greenhouse gas emissions (GHGE). The observed strong increase in atmospheric greenhouse gas concentrations in the last century results to a substantial degree from the energy conversion system and the transportation sector (Houghton et al., 2001).

To reduce the dependency of the energy sector on the use of fossil fuels and therefore reducing GHGE in the future, one of the key challenges is the reorganization of the global energy system. Policy-makers and utilities, thus, are today facing the challenge to predict the potential of different technologies to meet the requirements of a sustainable and environmentally benign energy system in the long term, while at the same time maintaining current high standards in energy conversion at affordable economic costs. Policy makers need to decide on development strategies in order to pave the way towards a sustainable energy system, and on how to support most promising technologies. Utilities, on the other hand, are involved players in the development of strategies and their implementation and are finally required to adapt to the according changes.

It is the motivation of the author to analyze possible future scenarios of the European energy sector in the context of achieving a sustainable

energy system in the future. By analyzing the threats to the energy system due to climate change and the according impacts, the basis is set to compare the outcome of such analysis with energy systems development strategies which are designed to achieve a more sustainable energy system with low GHGE. This challenging task goes along with a high level of uncertainty and especially towards the long-term consequences – be it cost or benefits – of such fundamental changes in energy system paradigms.

1.2. Scope of Analysis

To achieve stringent greenhouse gas emission reductions in the future, the competitiveness of different technological options with respect to cost parameters, potentials and emission savings needs to be understood to identify possible bottlenecks in the implementation of climate mitigation targets. This dissertation aims at presenting different strategies for the European energy conversion sector to comply with different emission targets under a set of additional policy constraints in order to strive for a sustainable energy system. In research on mitigation targets the related costs and long-term effects on the energy system are presented, including the role of different renewable energy potentials.

Additionally, the potential threats of climate change on the energy system are analyzed to appraise the impacts of not mitigating climate change in the future. This research is of high importance to disclose possible adaptation measures and consequential costs which are needed to compensate inaction in reducing GHGE.

1.3. Methodology

For the analysis of the future energy system transformation under a given set of constraints (e.g. greenhouse gas emission reduction targets), the European Multi-regional MARKAL model (EuroMM) was developed on the basis of existing modeling tools currently applied at the world level (Barreto and Kypreos, 2004; Criqui et al., 1999). EuroMM, which is part of

the MARKAL family of models, is a partial-equilibrium, bottom-up model with a detailed representation of energy technologies (Loulou et al., 2004) and serves for the analysis of the European energy system by investigating the impacts of different climate policies in a scenario approach. The model EuroMM describes the actual technology mix for energy conversion and the related CO_2-emissions as well as new technologies which are expected to be available in the future. Special emphasis is put on the implementation of the electricity sector with detailed accuracy in comparison with existing models, e.g. described in Mantzos et al. (2004).

For the purpose of this analysis, the technologies involved are analyzed and characterized in terms of costs and potentials in order to provide an adequate representation of competing pathways in the energy conversion EuroMM model. Potential competitors in the electricity generation and fuel production sectors are identified and included in the analysis, and the impacts of different policies on the diffusion of cleaner technologies into the EU energy system are also investigated.

1.4. Structure of the thesis

After this short introduction (chapter 1), the motivation to this dissertation is further elaborated in chapter 2, by introducing climate change science in a broader context. This chapter gives an overview of parameters related to climate change such as the theory of radiative forcing and anthropogenic greenhouse gas emissions which are important to understand the need for emission reduction targets. Furthermore, the direct impacts of climate change on the energy conversion sector are introduced and mitigation options to reduce climate change impacts are described.

In chapter 3 the modeling framework is described, which is used for the analysis of the future European energy conversion sector. This includes the setup of EuroMM, the basic assumptions (e.g. regional disaggregation, technologies, etc.) and special features of the model (e.g. electricity grid, seasonal demands). Additional, a business as usual scenario is presented (baseline) which describes a possible development of the energy sector without consideration of climate change impacts or mitigation tar-

gets. This baseline scenario is used as reference for the assessment of the different climate change scenarios.

The climate change threats relevant to the energy conversion sector are further introduced in chapter 4. This includes estimates for changes in air and water temperatures as well as changes in precipitation which influence the energy conversion sector. The results presented in this chapter include the first estimates available on costs of adapting the energy conversion sector to climate change on European scale. This chapter concludes with a discussion about further possible impacts of climate change and implications for policy makers.

The options for mitigating climate change are then presented in chapter 5. Given two different emission targets for Europe, results are presented which show possible pathways for the energy conversion sector to comply with stringent climate targets. Two different targets are analyzed which are assumed to stabilize global temperatures below 2°Celsius in 2100 with a probability of either 50% or 80%.

In chapter 6 different technological parameters and possible political constraints are further analyzed to depict pathways towards a sustainable energy conversion sector. Under special consideration in this chapter are different electricity generation technologies such as wind power, nuclear power and fossil generation technologies with carbon capture and sequestration facilities. These three major groups of power generation technologies are expected to have a high potential for reducing GHGE in the future. This chapter is closed with a discussion about the different constraints included in the scenario analysis.
A summary of the findings and final conclusions are presented in chapter 7 wherein which the analysis and results included in this dissertation and final remarks and implications are outlined for the reader.

2. Challenges for the European Energy Conversion Sector

To analyze future scenarios of the European energy conversion sector under given climate change scenarios, it is important to understand the historical development of the energy sector as well as to understand the linkages between energy conversion, emissions and climate change. Furthermore, it is important to understand the challenges which arise due to the above mentioned linkages as well as to understand other challenges which are influencing the future development of the energy sectors. To give a broad overview of these issues, this chapter is organized as follows: In section 2.1, an overview of the historical development of the energy conversion sector in Europe is given, defining the system from which on the future energy infrastructure is developed. In section 2.2 the so called conventional challenges independent of climate change are introduced, including topics such as projected increasing final energy demands, the aging of the European energy infrastructure and the depletion of domestic fossil resources, among others.

Special emphasis is put on the challenges from climate change which are outlined in section 2.3. This section starts with a description of the physical science base of climate change and the relation to GHGE (subsection 2.3.1). Furthermore, the historical CO_2-emission development and future projections for this specific greenhouse gas (GHG) are described (subsection 2.3.2 and 2.3.3, respectively) to link to the challenges from rising GHGE and climate change (subsection 2.3.4). In subsection 2.3.5, possible climate change mitigation options are introduced to outline the efforts needed to reduce GHGE in the future.

This chapter is then closed by section 2.4 discussing the importance of different technology options and policies for the energy sector to address

the afore described challenges in the energy conversion sector.

This chapter focuses on Europe but it is needless to say that the issue of climate change can not be seen from an European perspective only. Therefore some linkages are shown between Europe and other world regions.

2.1. The European Energy Sector Today

2.1.1. Energy Conversion

The European energy conversion sector as it is described in this dissertation, includes major processes which transform primary energy carriers (e.g. coal, oil and gas) into secondary energy carriers (e.g. fuels and electricity). These processes include heat and power generation, fuel production and the retrieval of coke and other coal products independent of the primary energy source. The total primary energy supply (TPES) in Europe (comprising EU27 plus Norway and Switzerland) in the year 2005 was estimated to approximately 83 exajoules (EJ) and from which almost 80% of it was based on fossil fuels (see figure 2.1). The main share of TPES (almost 38%) was covered by crude oil used for fuel production. Focusing on the electricity sector, it was found that almost 20% of TPES was used for electricity generation based on fossil fuels whereas 10 EJ from TPES (almost 13%) were for nuclear based electricity generation (EIA, 2006).

In terms of electricity generation, the share in coal (hard coal and lignite) and natural gas based generation contributed with 28% and 19% to the total electricity output, respectively. The single largest contribution with 28% of total electricity generation was based on nuclear fuel in 2005. Looking at the historical development of electricity generation in Europe (see figure 2.2) an increase of almost 30% in total production over the last 15 years occured. It is interesting to see that almost 65% of the additional electricity generation in 2005 compared to 1990 was based on natural gas. The reasons for this are the lower overall pollution of burning natural gas compared to other fossil generation, the low capital
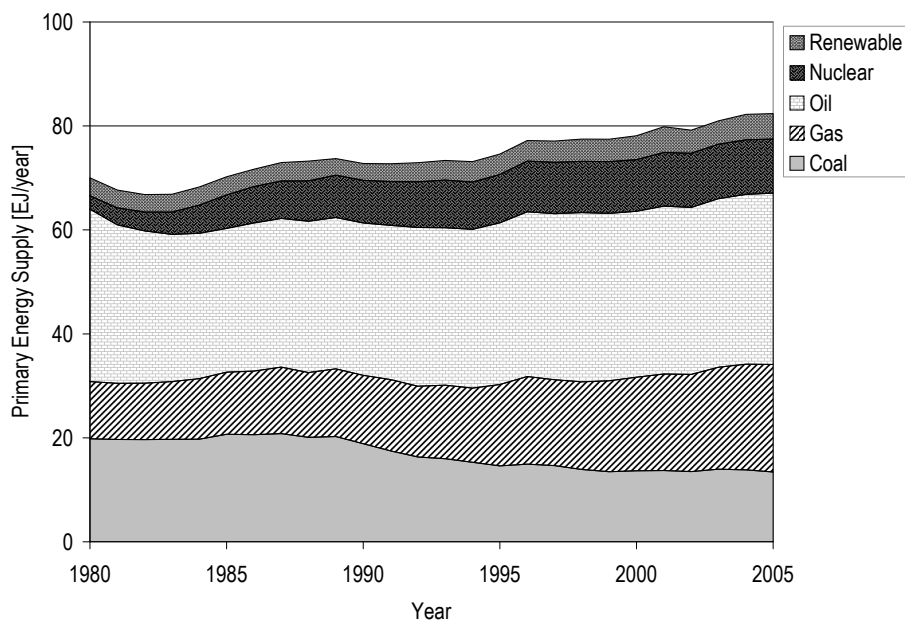
FIGURE 2.1.: *Historical development of primary energy supply of EU27 (EIA, 2006). EU27 includes all member states of the European Union in the year 2005.*

intensive generation technology available on the market and the relatively low market prices for natural gas in the 1990s. Additional investments in the transmission and distribution infrastrucutre for natural gas made this type of power generation highly competitive (EEA, 2006). Due to this increase of natural gas used in electricity generation, the GHGE from the public power generation sector in the considered time period were reduced (EEA, 2006). However, the strong increase in the use of natural gas for electricity generation as well as the increase in demand for final energy purposes concentrates the European import dependancy for the specific fuel, since the indigenous production of natural gas decreases at the same time (Kjärstad and Johnsson, 2007*b*).

Given the high import rate for fossil fuels in Europe and the issue of climate change, strong efforts are needed in the near future to reduce
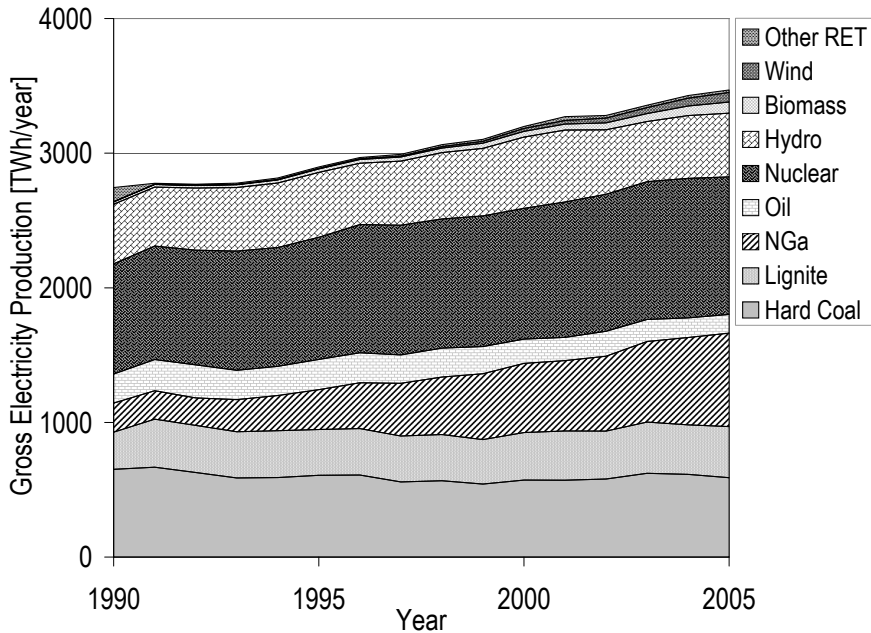
FIGURE 2.2.: *Historical development of electricity production by fuel in EU27+2 (EEA, 2006). NGa stands for natural gas based power generation, other RET defines other renewable energy technologies including geothermal electricity generation as well as solar PV electricity generation.*

the dependency on carbon based fuel technologies. With the European climate target of 2 °C (European Commission, 2007b) (see also subsection 2.4.1) the analysis of emission scenarios for 450 ppm CO_2-eq and 400 ppm CO_2-eq become more relevant. In the subsection 2.3.2, the historical development of GHGE in Europe and the world is introduced to further link to questions about climate change. However, not only the high contribution of the energy sector on climate change is crucial but also the fact that the energy sectors are vulnerable to rises in global temperature (Parry, 2000) (see chapter 4).

2.1.2. Final Energy Demand

Final energy demand is the sum of all energy demands arising from activities in various sectors which are providing services and/or products. The demand for energy carriers varies across sectors from the oil based transportation sector to the services sector which mainly relies on electricity and natural gas as input fuels. The increase of electricity generation over the last 15 years (see figure 2.2) was mainly due to rising demand in the residential and services sector (EEA, 2006). With a growth of almost 40% over this period, the residential and services sector increased its share in total final energy demand from 43% to 47% and is therefore the only sector which has increased its share in total demand. The industrial and energy sector reduced their share by 3% and 1% (percentage points), respectively. The transportation sector only covers a small fraction of total electricity demand with approximately 2.3% (EEA, 2006).

In the last 15 years, the final energy demand for oil and oil products in the final energy demand sectors industry, service, residential and transport rose by 13% from approximately 18 EJ to 21 EJ in 2005. However, the various sectors show different trends in demand over the given time horizon. While the demand in the transport sector grew by 27% from 12 EJ in 1990 to above 15 EJ in 2005, all other sectors show a decline in the demand in the range of percentage points 8-23% (EEA, 2006).
Final energy demand for natural gas declined in the last 15 years from 11 EJ to about 8 EJ by approximately 24%. The industry sector showed a relative stable demand of 4 EJ over the observed time horizon, while the other demand sectors (transport, household and services) exhibited declining demands for natural gas (EEA, 2006).

2.2. Future Challenges and Developments

In this section some of the future challenges for the European energy conversion sector are introduced. The collocation of challenges described here is by no means comprehensive, since it is intended to give a broad overview of relevant topics which are important for the development of the European energy sector. However, not all of the described challenges are

included in the model analysis which is described in this dissertation.

2.2.1. Demand Changes

As shown in section 2.1.2, final energy demand for electricity and transport fuel rose in Europe in the last years continuously. This growth in demand was balanced by an increased use of fossil sources, leading to slight increase in greenhouse gas emissions (see section 2.3.2). For the future, different scenarios for the development of electricity demand and other energy carriers are available in the literature. A majority of the model based scenario analyses expect that electricity demand in Europe as well as other world regions will continue to grow in the future due to various reasons (e.g. economic growth, population growth and higher standards of living, among others (European Commission, 2006b; IEA, 2008; Mantzos and Capros, 2005)) leading to higher values for the total primary energy supply. However, other studies exist which depict possible pathways for reduced energy demand developments (Benoit and Comeau, 2005; Teske et al., 2007).

Given the differences in model assumptions in the various models mentioned above, the difficulty arises to identify key scenario drivers for energy demand projections to extract relevant conclusions for future policy interventions. For instance, Mantzos and Capros (2005) and Teske et al. (2007) use different country aggregations and different scenario drivers such as GDP-growth[1] which lead to different model outcomes. Additional, the assumptions on changes of the energy intensity (energy demand per unit of GDP) vary accross models over the considered time horizon in different model analyses, and therefore energy demand differs across models. A more comprehensive analysis of different model assumptions and key scenario drivers was recently presented by Ruoss (2009, Master Thesis).

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[1]Mantzos and Capros (2005) depict possible energy pathways for different country aggregations such as EU-25, EU-27 and EU-30 using 1.85% GDP per capita growth per year in EU-25, while Teske et al. (2007) use 1.7% GDP growth values with power purchaising parity (PPP) exchange rates for OECD-Europe.

These different future scenarios for energy demand imply two challenges for the development of the energy system. If the historic development of final energy demand is extrapolated into the future, additional efforts are needed to develop a sustainable energy system in the future. Under the assumption of increasing energy demand, not only the current level of energy needs to be supplied by a more sustainable energy system, but also the additional demands will have to be covered by such system.

The alternative challenge is to break the historical trend of increasing energy demand by the implementation of policy and technology measures to increase energy efficiency. As described in Jochem et al. (2000), the potential for energy savings in all demand sectors is huge, but additional efforts are needed to realize further energy savings. It is noteworthy that already in the past, large efficiency improvements were achieved, but nevertheless further efforts are needed to accelerate the reduction of energy intensity in the future.

2.2.2. Infrastructure

One relevant factor in respect of future scenarios for the power generation sector is the residual lifetime of power plants. In Europe, approximately 30% of the total installed thermal capacity is older than 30 years and another 40% is older than 20 years (Kjärstad and Johnsson, 2007*a*). Given an average technical lifetime of 40 years for existing power plants, this implies that in the next 20 years more than 60% of the thermal generation capacities need to be replaced. This necessity for investments in new capacities is important to address the issue of reducing GHGE from the energy sector in the future (see subsection 2.3.3). By replacing fossil based generation capacity with renewable capacity, further steps towards a sustainable energy system can be taken. However, due to the nowadays higher specific generation cost for renewable electricity, further efforts are needed to increase market penetration rates of renewable technologies. Additionally, if electricity demand is growing in the future (see section 2.2.1), extra investments are needed for additional generation capacity to cover increasing demands.

A further challenge for the infrastructure arises based on different specifications of thermal technologies versus renewable technologies. While thermal capacity is mainly centralized in large units for base load generation, new renewable technology systems (e.g. solar PV, biomass based electricity generation, wind parks onshore, among others) are often installed as decentralized small units based on intermittent sources. Therefore, efforts are needed to strengthen grid infrastructure to allow both systems to interact for covering electricity demand. The development of so called "smart grids" is a potential way of achieving such grid infrastructure (see European Commission (2006a) for further information).

2.2.3. Uncertainty of Technologies Available

Given the large need to update the energy infrastructure in the future, the likely increase in electricity demand and the need to switch the energy system towards a system with low greenhouse gas emissions, the technological options to overcome such challenges are crucial. Nowadays, decision makers discuss three major technologies and technology pathways which are considered as potentially feasible for resolving these issues.

Nuclear power, especially based on advanced technologies is considered as one of these options. The advantage of new nuclear power is the low greenhouse gas emission rate per electricity output and the design for a large output of base load electricity. However, safety issues, high capital cost and unresolved questions about waste disposal are disadvantageous for the installation of new nuclear power. Additionally, the ongoing construction sites in France and Finland for advanced reactors are over budget and are lagging behind schedule which in general will delay the rapid deployment of installations in the future. Although it is likely that such problems can be resolved in the future, a wide range of policies and support measures will be necessary to overcome these challenges. However, it is uncertain if public and market barriers can be settled in reasonable time.

A further technology which is considered as key technology for generating low emission electricity is carbon capture and sequestration (CCS) for fossil based power plants. Although the technology for CCS-systems has been used in oil and gas fields since the mid 1990s (e.g. in the Sleipner gas field in Norway), several challenges need to be resolved in the future, for deploying CCS-technologies in large scales. As described by Odenberger et al. (2008), enough storage capacity for CO_2 is available across Europe for large amounts of captured gases. However, it remains open if these potential storage sites can be fully accessed and if the long-term storage of greenhouse gases can be guaranteed. Leakage from such storage-sites potentially leads to fatalities and could compromise climate change mitigation. Additionally, the cost of CCS-technologies remain relatively high since infrastructure investments are necessary for pipelines and pressure pumps to transport CO_2 from the site of emission to the storage site.

Nowadays only test plants are available for demonstration reasons and the technical feasibility of large scale power generation with CCS needs to be proven. Again, supportive policies and financial incentives are necessary to allow for a rapid deployment of fossil based generation with CCS.

Renewable technologies such as wind power and solar PV saw a rapid increase in installed capacity over the last years. However, increasing shares of renewable technologies with intermittent characteristics in the grid infrastructure pose some challenges for managing electricity demand and supply in real time. Large backup-capacities are likely to be needed to prevent downtimes in electricity generation if intermittent sources are not available. Besides these rather technical constraints further policy support is needed to allow for further deployment of renewable technologies.

2.2.4. Depletion of Domestic Resources

Depleting fossil sources for energy purposes are a crucial factor for electricity and fuel generation in the future. Depending on the fossil source which is under consideration, different levels of available resources are

considered for oil, gas and coal on global scale. While from these sources mainly gas and oil are expected to face a decrease in production over the coming decades, coal is a more abundant source for energy purposes (WEC, 2004). However, the depletion of oil and gas resources is especially important for Europe which already today faces declining production of natural gas in some member countries (e.g. United Kingdom (UK), Germany and Italy). Since natural gas is important for electricity production as well as for heat generation with relatively low emissions compared to hard coal and lignite, depleting domestic natural gas resources are likely to influence future energy provision in Europe. According to the report of the World Energy Council (WEC, 2004), the proven recoverable gas and oil resources for major producers such as UK and Norway are available for the next 10 to 30 years under the assumption of constant production rates (WEC, 2004). Due to expected increases in demand for such resources, rising natural gas imports are likely. However, it is expected that additional imports are accompanied with increasing fuel prices, which would therefore increase the price for electricity as well. Rising electricity prices may force power producers towards the use of cheaper energy sources such as coal and lignite. However, this would be in contrast to the overall goal of achieving a more sustainable energy system due to higher GHGE from coal and lignite based power generation. Additional concerns about increasing fuel imports are related to the security of supply which may be negatively affected since natural gas suppliers can not always be considered as reliable partners. Already today, Europe imports more than 30% of its natural gas demand from countries such as Russia or Algeria and a decreasing domestic production would increase the import dependency if lower domestic production can not be compensated by a reduction in demand.

2.3. Challenges from Climate Change

2.3.1. Summary of the Physical Science Basis

In the last decades of the 20th century, the issue of rising greenhouse gas emissions and their impact on Earth's climate became an important research topic. With the publication of the first Assessment Report of

the Intergovernmental Panel on Climate Change (IPCC, 1990), the inter linkages between increasing human induced GHGE and climate change (greenhouse effect) were brought to the public. To assess this relation, the concept of radiative forcing (RF) was introduced (IPCC, 1990), which includes the important assumption that climate change is proportional to radiative forcing (Hansen et al., 1997).

Radiative forcing is defined as the change of the global average net radiation in the tropopause (Houghton et al., 1995). This means that in an unperturbed state of the atmosphere the net incoming solar radiation is balanced by the net outgoing infrared radiation (Houghton et al., 1995). One of the characteristics of greenhouse gases is to trap and absorb infrared radiation. With increasing GHG concentrations, the net outgoing radiation is reduced which is described by a positive radiative forcing. To restore the equilibrium between incoming solar radiation and outgoing infrared radiation, the temperature of the troposphere and the earth surface must increase, thus producing an increase in the outgoing radiation (Houghton et al., 1995). The radiative forcing varies, depending on the characteristics of the greenhouse gases. For the most relevant greenhouse gases the equations to calculate the radiative forcing ΔF and therefore the mean surface temperature change ΔT_s is given in the equations 2.1 and 2.2, respectively (Houghton et al., 2001; Myhre et al., 1998).

$$
\begin{aligned}
\Delta F_{CO_2} &= \quad \alpha \ln(C/C_0) \\
\Delta F_{CH_4} &= \quad \beta(M^{1/2} - M_0^{1/2}) - (f(M, N_0) - f(M_0, N_0)) \\
\Delta F_{N_2O} &= \quad \varepsilon(N^{1/2} - N_0^{1/2}) - (f(M_0, N) - f(M_0, N_0)) \\
f(M, N) &= \quad 0.47\ln(1 + 2.01 * 10^{-5}(MN)^{0.75} + 5.31 * 10^{-15}M(MN)^{1.52})
\end{aligned}
$$

$$
\begin{aligned}
\alpha &= \quad 5.35 \\
\beta &= \quad 0.036 \\
\varepsilon &= \quad 0.12
\end{aligned}
$$

$$
\tag{2.1}
$$

$$
\Delta T_s = \lambda \Delta F \tag{2.2}
$$

These equations are valid for well mixed gases and with a given uncertainty of $\pm$ 10% for the radiative forcing (Houghton et al., 2001). The val-

ues C_0, M_0 and N_0 indicate the greenhouse gas concentration in the year 1750 for CO_2, CH_4 and N_2O, respectively. These values are assumed to be the unperturbed concentrations of greenhouse gases before the industrialization.

Since 1750, the increasing GHG concentrations are mainly based on anthropogenic emissions from the burning of fossil fuels and land cover changes (IPCC, 1990). The concentration of CO_2 increased from about 280 ppmv in 1750 to about 380 ppmv in 2005 and shows a tendency to continuously increase. Growing concentrations of CH_4 and N_2O are also observed, although on lower levels[2]. The total greenhouse gas emissions lead to an average radiative forcing of approximately 2.6 W/m^2 until 2005 which translates into a global warming of 1.3 °C during this period (using the climate sensitivity parameter $\lambda = 0.5\,K/(Wm^{-2})$, (Ramaswamy et al., 2001).

However, to fully understand the interlinking between GHGE, GHG concentrations and the measured radiative forcing levels and temperatures, it is necessary to understand that other parameters in the carbon cycle and the radiative forcing concept exist, which reduce climate change. For the carbon cycle, carbon sinks such as the oceans or growing forests can reduce GHG concentrations due to their uptake of CO_2. It is estimated that the annual ocean uptake rate for CO_2 is in the range of 2.2 $\pm$ 0.5 Gt. With increasing temperatures, this uptake rate is likely to decrease in the future, leading to higher remaining atmospherical CO_2 concentrations (Denman et al., 2007). Overall, the terrestrial biosphere and the oceans have removed 45% of fossil based CO_2 emissions during the last 45 years (Denman et al., 2007). In general, it is estimated that approximately 50% of an increase in CO_2 emissions is removed after 30 years from the atmosphere whereas the other 50% remain in the atmosphere for centuries or even many thousands of years (Denman et al., 2007).

---

[2]From 1979 measurements of GHG are based on the NOAA global network (U.S. Department of Commerce - National Oceanic and Atmospheric Administration - Earth System Research Laboratory - Global Monitoring Division). Older data is based on ice-core measurements (IPCC, 1990).

For the radiative forcing concept, different types of forcing exist, such as the cloud albedo effect, the direct effects of aerosols and other aerosol-cloud interactions, as well as the impact of hydroxyl free radicals which are directly or indirectly influencing the radiative forcing (Forster et al., 2007). For these different types of forcing, positive as well as negative values are found, which therefore increase or decrease ΔF.

One further limitation of the radiative forcing concept is that it can not be used exclusively to assess the potential climate change from emission sources. This is due to the fact that the RF-concept is used to display the actual radiative forcing for specific gas amounts (Ramaswamy et al., 2001). Therefore, the global warming potential (GWP) is used to show the integrated relative effect of a gas over its lifetime compared to CO_2 (see equation 2.3, where TH is the observed time horizon, a_x is the radiative efficiency depending on the lifetime of the gas, and [x(t)] is the time-dependent decay of the compound (Ramaswamy et al., 2001)). In the denominator, the corresponding quantities for the reference gas are given. The lifetimes of non-CO_2 greenhouse gases are largely dependent on the atmospheric photochemistry and vary between less than 1 year to up to 10'000s of years (Ramaswamy et al., 2001).

$$GWP(x) = \frac{\int_0^{TH} a_x * [x(t)] dt}{\int_0^{TH} a_r * [x(t)] dt} \qquad (2.3)$$

This short introduction of the physical science basis of climate change is the foundation to discuss the uncertainty in climate projections, as well as to derive climate mitigation targets in the subsections 2.3.4 and 2.3.5, respectively. Next, the historical emission development is introduced, as well as future emission projections to outline the challenges from climate change in the future.

2.3.2. Historical Emission Development

As introduced above, the atmospheric CO_2 concentrations rose from approximately 280 ppmv in 1750 to more than 380 ppmv in 2005. A large share of these human induced GHGE (mainly CO_2) is based on the com-

bustion of fossil fuels with major increase of emission in the last decades. Since the 1980s, these emissions grew continuously on world level (figure 2.3). In 2004, the burning of fossil fuel for power generation contributed with approximately 26% to total GHGE. Emissions from electricity generation grew by more than 145% from 1970 on to actual emissions of approximately 11 Gt of CO_2 per year (Rogner et al., 2007). Analyzing the emissions from fuel combustion in more detail, some differences in emission growth between regions can be found. The Asian & Oceanic (A&O) region (including China, India, Japan and Australia as main emitters EIA (2008)) shows a strong increase in emissions from the early 2000s on, whereas almost all other world regions show a linear increase during the same years. These rapid growing emissions in A&O reflect the high economic growth and population increase in countries such as China and India (see figure 2.3). Coinciding with the changes in growth in Asia and & Oceania from 2000 on, the carbon intensity (CO_2 emissions per unit of primary energy supplied) increases since the year 2000 as well, in contrast to the years from 1979 until 2000, where a declining trend in the carbon intensity was observed, offsetting partly growing CO_2 emissions. This trend in increasing carbon intensity indicates that more resources with higher emissions per output of energy are used due to declining production rates of more efficient resources. Additional, the effects of efficiency gains in energy supply and demand, and reductions in the emission intensity (emissions per unit of GDP) were not strong enough to offset increasing GDP and population effects (Rogner et al., 2007).

However, not only GHGE from fossil fuel combustion increased, but also other emissions from sectors such as agriculture, land use and land use change or forestry (LULUCF), contributed by approximately 30% to total greenhouse gas emissions in 2004. Additional, while low in terms of mass, the emissions of fluorinated gases (including SF_6 which is used for the insulation of high voltage electricity cables) are concidered as harmfull due to their high global warming potential (GWP) (see section 2.3.1).

This general trend of strongly increasing GHGE in recent decades, is important for the future development of the Earth's climate. Since approximately 50% of these emissions will remain in the athmosphere for
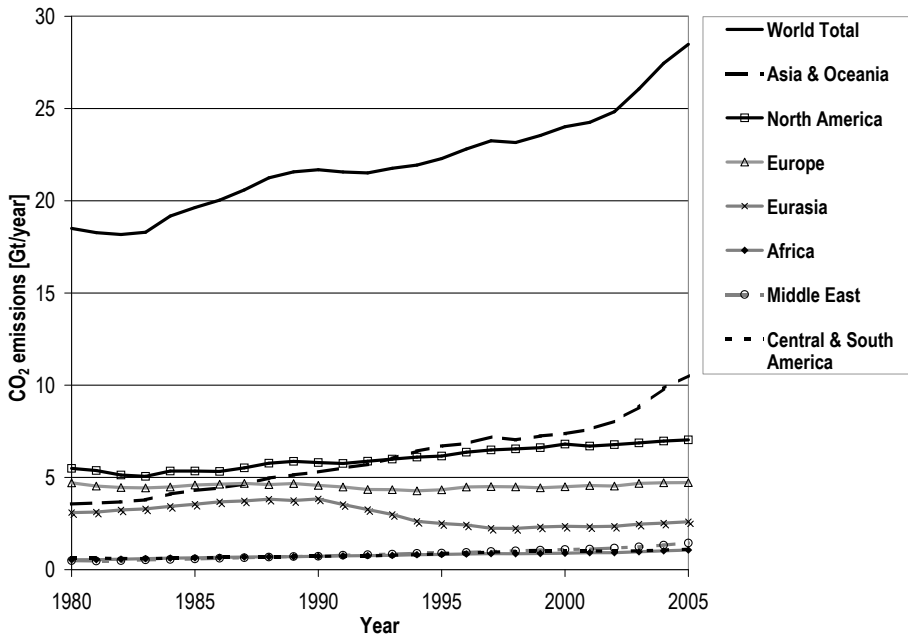
FIGURE 2.3.: *Historical CO_2 emissions for the world and selected world regions from the combustion and flaring of fossil sources (EIA, 2008).*

more than 100 years (Denman et al., 2007), they continue to contribute to higher global temperatures due to the fact that the radiative forcing is increased.

2.3.3. Future Emission Projections

Given the anthropogenic GHGE emitted from the 1750s until today, the question arises, which level of emissions are expected for the future and how they influence our climate. Given the growing world population which is estimated to reach approximately 9 billion in 2050 (United Nations, 2005), it is likely that global GDP will increase in the future. Since there is a strong relation between GDP and final energy demand (Dincer and Dost, 1997), it is highly probable that GHGE from fossil fuel combustion will continue to rise in the future in absence of mitigation policies (Rogner et al., 2007). According to the estimates of the United Nations (United Na-

tions, 2005), most of the population growth will take place in developing countries. To cover the growing energy demand in these regions, it is estimated that e.g. approximately 750 GW of coal fired power plants with high CO_2 emissions will be built in countries such as China and India in the next 30 years (IEA, 2003). This is in line with the general trend of continued dependency on fossil fuels (Rogner et al., 2007). According to Unruh and Carrillo-Hermosilla (2006), it is unlikely that developing regions will "leapfrog carbon intensive energy development" although concerns about climate change rise. In this context it is important to see that the lock-in effect which has arisen due to the past investments in CO_2 intensive infrastructure plays a major role in estimating future GHGE (Unruh and Carrillo-Hermosilla, 2006). However, many attempts were undertaken to estimate the future GHGE and an overview of different scenarios was presented in the 4th Assessment Report of the IPCC (Bernstein et al., 2007). These scenarios show a band of temperature changes of 1.8 °C up to 6 °C and more until 2100, compared to pre-industrial levels. In these scenarios, all GHGE from various sources are included.

There are two possible ways of coping with the future which is described by the various scenarios for greenhouse gas emission development, namely "Action" and "Inaction" (Bernstein et al., 2007). Action refers to the possibilities of reducing future GHGE by technical and political measures to limit climate change and will be further discussed in section 2.3.5. Inaction refers to growing GHGE without mitigation efforts. The expected implications of inaction are further analyzed in section 2.3.4.

2.3.4. Climate Change Impacts

General Impacts

Rising greenhouse gas emissions influence the physical balance of the Earth system. This change can be expressed by the increase of the radiative forcing, or through higher air temperatures. Rising temperatures though influence other climate elements of the Earth system such as the air pressure or atmospheric moisture. The sum of all climate elements and their longterm changes due to higher temperatures are the foundation for irrevocable damages to the established climate system.

As feedback from the changing climate system, damages to other ecosystems are observed and expected to increase in the future. In recent years, many efforts were undertaken to analyze and quantify these damages which reach from local, small scale impacts on single creatures to global changes of the living environment. A broad overview of these negative impacts is given by the working group II of the IPCC in its contribution to the fourth Assessment Report "Impacts, Adaptation and Vulnerability", which is summarized in (Parry et al., 2007). Major systems under threats from climate change are the freshwater system, agricultural systems regarding food supply, coastal systems due to rising sea levels and the human health, among others (see also (Ciscar et al., 2009; Lehner et al., 2005; McMichael et al., 2006; Parry et al., 2004)).

A challenging issue regarding climate change is the variation of impacts and damages across world regions. While developed regions may have the economical potential to reduce climate change impacts by adaptation measures, less developed regions are more likely to face higher stress to cope with climate change. The United Nation Framework Convention on Climate Change (UNFCCC) estimates the overall adaptation cost for all sectors investigated for the year 2030 in the range of approximately $50-$170 billion per year (UNFCCC, 2007) and thereof $30-$130 billion is likely to be needed for the adaptation of the infrastructure. However, the uncertainty of these cost estimates is large due to the underlying assumptions and according to Parry et al. (2009), the estimates from the UNFCCC study underestimate adaptation costs by a factor of 2 to 3. Additionally, the UNFCCC study (UNFCCC, 2007) only reports cost estimates for the year 2030, and it is expected that adaptation cost will continue to rise (Parry et al., 2009).

Environmental Impacts Relevant for the Energy Sector

Some of the impacts of climate change which are described in the fourth Assessment Report of the IPCC (Bernstein et al., 2007) are of major relevance for the energy conversion sector. One of the possible impacts of climate change on European level was described by Arnell (1999) and

Lehner et al. (2005), concerning the runoff of rivers. This parameter is of importance for the energy sector since large amounts of waters are used for cooling purposes in power plants as well as used for power generation in hydro power plants. Both, Arnell (1999) and Lehner et al. (2005) state that the total runoff of rivers will change, depending on the geographical latitude. The authors expect that southern European regions will see lower river runoff while northern Europe is likely to face higher river runoff (Arnell, 1999; Lehner et al., 2005). Therefore, higher potentials of hydro power are likely to occur in northern European countries and reduced potentials are to be expected in southern Europe. Regarding the future changes in hydro runoff, it needs to be considered that all given numbers for future runoff under different scenarios underly uncertainties which need to be quantified for each region separately (e.g. for Switzerland these uncertainties are described in Schaefli et al. (2007)). However, the data regarding uncertainties for river runoff is still scarce for some European regions.

As mentioned above, rivers are often used for cooling purposes in large power plants. In case of droughts and periods of low river flows, it is expected that power producers will face water shortages for cooling purposes. During drought periods, regional water management is becoming more important since other sectors with high water consumption compete for the same resource (Iglesias et al., 2007). Therefore, in periods of low river flows, power output of thermal power plants might need to be reduced.

In addition to the changes in the annual river runoff, also the seasonal distribution of high-, average and low flow of rivers will change (Arnell, 1999), which leads to changes in the seasonal utilization of hydro power plants. According to Arnell (1999), climate change will significantly affect the snow cover in the spatial distribution and total amount. Eastern Europe for example will see reduced snow cover in winters, leading to lower spring flows due to snow melt but higher winter runoffs due to precipitation falling as rain instead of snow (Arnell, 1999).

As one of the most important physical properties relevant for the en-

ergy sector, the water temperature will also be affected by climate change (Webb, 1996). During the last century it is estimated that European average river temperature has increased by 1 °C (Webb, 1996). This trend will continue in the future and is likely to be more pronounced. This is of relevance since higher water temperatures, especially in summers, influence negatively the efficiency of power plants (Durmayaz and Sogut, 2006). However, more important are higher temperatures in context of European environmental regulations which limit the water temperatures of rivers which are allowed for cooling purposes (see European Freshwater directive, (European Council, 2006)). If certain threshold temperatures are reached in rivers, power producers need to reduce the consumption of water for cooling purposes.

There are other factors which are also likely to influence the energy conversion sector and in some cases data is available about the level of changes which will occur. Among these factors are the changes in average wind velocity, the return rate of extreme events such as heat waves, droughts, heavy storms and floods as well as the possible changes in cloud cover and therefore changes in incoming solar radiation for solar electricity generation (Easterling et al., 2000; Parry, 2000). In general it is expected that the return period of extreme events will shorten due to climate change (Parry et al., 2007) and in case of the return period of flood events and droughts, consistent results are published (Dankers and Feyen, 2008; Lehner et al., 2006; Milly et al., 2002). While the changes in average wind velocity and heat waves and droughts are more likely to influence the potential for electricity generation, other extreme events such as heavy storms and floods are more likely to impact the energy infrastructure. However, it remains unclear to which extent these impacts effect the energy system in terms of cost.

One additional minor factor which also needs to be considered in this respect is the higher resistance of transmission lines due to increased air temperatures (Zhelezko et al., 2005), leading to higher transmission losses.

Adaptation of the Energy Sector

In the case of climate change (independent of the level of global temperature increase), adaptive measures need to be considered to avoid serious damages in such various dimensions as described above. The relevance of the adaptation issue for Europe has recently been recognized by the European Commission (European Commission, 2007a) and several sectors were identified to be considered for adaptive measures. One of these sectors is the energy conversion sector, including transmission and distribution infrastructure (European Commission, 2007a). However, only examples of possible adaptation measures of the energy sector are given for Europe and other world regions (Bernstein et al., 2007; European Commission, 2007a), such as the diversification of energy sources or the development of renewable sources, among others.

The situation of possible low output of power plants due to the above mentioned impacts of climate change are likely to coincide with higher demands for electricity in summers due to increased demands for space cooling (Cartalsi et al., 2001; Franck, 2005; Ruth and Lin, 2006). Therefore, it is expected that additional generation capacity would be necessary to cope with these impacts. Additionally, the reduction of runoff and high water temperatures may lead to the refurbishment of existing power plants by installation of advanced cooling systems to prevent shortages of cooling water availability (see chapter 4).
To protect the energy infrastructure from damaging extreme events such as heavy storms and floods, additional investments will be necessary to enforce dams and electricity transmission infrastructure.

2.3.5. Challenges from Avoiding Climate Change

Climate Change Mitigation

To prevent serious damages from climate change in the earth system, policy makers and climate scientists have been discussing GHGE reduction targets since the early 1990s. It is found that the guiding principle for climate change mitigation is the target of limiting temperature increase to below 2 °C, relative to pre-industrial levels (European Commission,

2007b; Meinshausen et al., 2009). Several attempts are proposed to achieve this target by either setting GHGE targets, GHG concentration limits or even temperature targets. However, this differentiation leads to the question of how this target can be defined in terms of allowed GHGE in the future and at which level the concentrations need to be stabilized to avoid serious damages to the earth system. The first part of this question about future allowance of GHGE was recently approached by Meinshausen et al. (2009). In a probabilistic analysis, the authors estimate the allowed amount of CO_2 emitted in the time between 2000 and 2050 from 1000 Gt CO_2 to 1440 Gt CO_2. If the amount of CO_2 emitted is higher than 1000 Gt CO_2 in the considered time period, the probability of staying below a 2 °C temperature increase is below 75%. If the probability of staying below 2 °C should be higher than 80%, the total emissions should not exceed 890 Gt CO_2 until 2050 (Meinshausen et al., 2009).

In respect of the concentration level which should not be exceeded for the 2 °C target, the IPCC estimats the CO_2 concentration to 350 ppm to 400 ppm (Fisher et al., 2007). Using the concept of radiative forcing introduced in section 2.3.1, concentration targets can be linked to the according temperature increase. However, a key uncertainty in different mitigation targets is the climate sensitivity (Fisher et al., 2007). Among other uncertainties in climate change processes, the climate sensitivity remains inadequately quantified (Forster et al., 2007) since feedback processes (e.g. clouds) which increase or decrease radiative forcing are not yet fully reproduceable by climate models (Randall et al., 2007). Therefore, by targeting stabilized GHG concentrations, the certainty of achieving these targets increases while the certainty about related climate change impacts decreases (Fisher et al., 2007).

However, the option of using temperature targets instead is less practical since the required emission targets are uncertain. According to Forster and Gregory (2006), the general understanding of climate change mechanisms has massively improved, but the uncertainty in climate change projections which are publicly available has refused to narrow.

Given the scientific targets for limiting GHGE mentioned above, action

from policy makers is needed to implement climate mitigation in national and sub-national regulations. Therefore, as one of the main contributors to past emissions, European policy makers have adopted the target of limiting climate change to below 2 °C temperature increase compared to the values before the industrialization and strives for strong action (European Commission, 2007b). As stated by the European Council (European Council, 2009), Europe commits to reduce emissions by 20% in 2020 compared to 1995 levels and is willing to increase the reduction target to 30% if other developed countries contribute to emission reduction as well. For the time until 2050 further emission reductions in the range of 60-80% compared to values of 1995 are considered by the European Council (European Council, 2009). However, the contribution of other developed countries as well as of developing countries is highly necessary since major increases of GHGE are expected outside of Europe (see section 2.3.3). In this dissertation, possible pathways for Europe to reduce emissions in the energy conversion sector by approximately 60-80% until 2050 are analyzed and described in chapter 5.

Besides the question about setting targets correctly and the commitments of policy makers, the cost issue of mitigation options is of major concern. Already in the negotiations to the Kyoto Protocol, decision makers were showing their high interest in the economic implications of mitigation measures (Manne and Richels, 2000) and it is noted down that measures dealing with mitigating climate change should be cost effective (Kyoto Protocol, 1998). However, as mentioned in the Stern review (Stern, 2006) the total cost of mitigating climate change is in the range of -2% to +5% of annual GDP until 2050 and is therefore much lower as compared to likely costs of adaptation.

Challenges for the Energy Sector

As described in section 2.1, the energy conversion sector highly depends on fossil sources and is one of the highest emitters of climate relevant GHG. To mitigate climate change, the energy sector would need to reduce GHGE by either switching to fuel sources with low or no CO_2 emis-

sions, such as renewables and nuclear energy, or large shares of emissions from fossil sources need to be captured and stored. For both cases, large investments in electricity generation capacity as well as alternative fuel production facilities are needed to change the infrastructure accordingly.

2.4. **Importance of Technologies and Policies**

2.4.1. **Climate Policies**

This ongoing growth in anthropogenic emissions is not consistent with the need to stabilize atmospheric GHG concentrations to prevent the earth from climate change. In the Kyoto Protocol (1998), which was the first attempt to act internationally to reduce climate change impacts, the international community agreed on stabilizing GHGE on levels below values from 1990. One part of the Kyoto agreement was that the countries named in Annex I of the UNFCCC should reduce their GHGE by at least 5% in the period from 2008 to 2012. However, not all countries named in this Annex I, ratified the Kyoto protocol until recently including large countries with high GHGE (e.g. USA, Australia). For developing countries (including China and India), no emission reduction targets were specified at all.

Due to low political and economical incentives to reduce emissions, the anthropogenic GHGE increase further and the country specific emission reduction targets listed in Annex B to the Kyoto Protocol (Kyoto Protocol, 1998) are far from being met. However, many policy makers and climate scientist urge for stronger actions in the future. In 2007, the European Union stipulated more urgent action by incorporating policies to stabilize climate change by 2 °C in 2100, relative to pre-industrial levels (European Commission, 2007b). The 2 °C target was set to limit the impacts of climate change and to decrease the probability of irreversible disruptions of the ecosystem (European Commission, 2007b).

However, this implies that the dependency on carbon based fuel technologies needs to be reduced, especially in the energy conversion sector. On the other hand many experts are doubtful if the 2 °C target corre-

sponding presumably to a concentration below 450 ppm CO_2-eq can be actually met. This statement is drawn from a poll published in April 2009 in "The Observer", which was interviewing climate scientists which participated in the climate congress in March 2009 in Copenhagen, Denmark. In this sense it is extremely important to understand that if policies do not change, the energy economy will not change and further depend by approximately 80% on fossil fuels (Rogner et al., 2007). To avoid such situation, ongoing negotiations are on the way to find a follow up agreement to the Kyoto Protocol (1998), including more binding targets and policies to prevent serious climate change.

2.5. Summary and Outlook

In this chapter, it has been shown that several challenges for the energy conversion sector need to be resolved in the future on the way towards a more sustainable energy system in Europe. Some of these challenges are specifically addressed in this dissertation and investigated using a modeling approach which is introduced in the following chapter. However, the main focus of this dissertation is on adaptation and mitigation strategies of the European energy conversion sector, to cope with challenges based on climate change.

Accordingly to the given introduction, adaptation and mitigation aspects should be considered in an integrated way (Klein et al., 2005). Looking at existing studies regarding mitigation and adaptation of climate change in the energy sectors, some studies deal with either of both aspects, as e.g. the World Energy Outlook of the IEA (IEA, 2008) and the Needs-study (Kypreos et al., 2008; van Regemorter, 2009), focusing on the quantification of mitigation aspects on global and European level by 2030 to 2050, or the PESETA-study (Ciscar et al., 2009) analyzing exclusively adaptation patterns of climate change. There are other studies which deal with both aspects in an integrated way, but cover only small model regions (Laukkonen et al., 2009). Attempts to quantify the impacts of adaptation to climate change and possible mitigation options in the energy sector on European level are still scarce. Therefore, it is the objective of this disser-

tation to examine in a quantitative way the adaptive needs in the European energy conversion sector until the year 2050 in case of increasing temperatures, and how it could look like under mitigation scenarios where climate change is restricted to below 2 °C temperature increase. This includes specific questions about impacts of rising temperatures on energy conversion technologies and the implementation of probable policy measures to limit climate change. One important parameter for the result analysis is the cost of either adapting to or mitigating climate change in the energy sector. With the outcome of this thesis it is intended to close a gap in estimating climate change adaptation costs which is described by (Parry et al., 2009), besides the description of mitigation pathways for the European energy conversion sector.

3. EuroMM - Modeling Framework: Scenario Development

3.1. Introduction

For assessing the future impacts of climate change on the energy conversion system and possible mitigation policies to develop a sustainable energy system, it is necessary to use models that simulate the long-term technological changes necessary to develop such energy system and are able to model changes in the environment.

In this context, a hybrid model system was developed within the European ADAM project, to investigate climate change impacts and adaptation measures as well as mitigation options which are relevant to strive towards a sustainable energy system in Europe. The overall objective of the ADAM project (ADaptation And Mitigation Strategies - Supporting European Climate Policy) was to support the European Union in the development of post-2012 global climate policies. The work described in Jochem et al. (2007) focused on the European energy sector, including macroeconomic developments, energy demand trends and supply options in light of CO_2 emission reduction targets and adaptation measures. To do so, different sectoral bottom-up models analyze sector specific energy demand trends and energy supply options. The models are soft linked via global parameters valid to all models, such as the CO_2 price in case of climate change mitigation, or macro-economic parameters, such as GDP per capita. These overall parameters were obtained by a global model including energy supply and demand in one. EuroMM, the model introduced in this dissertation was integrated in the above mentioned hybrid model system. The aim of EuroMM was, to bring together the results of the different bottom-up models describing future energy demands and resource potentials, and link these results with the energy conversion

sector. Building the synthesis of energy demand and supply scenarios, EuroMM describes possible pathways to achieve stringent emission reduction targets in the energy sector in Europe.

The advantage of this hybrid model approach compared to other global model approaches (e.g. POLES (Criqui et al., 1999) or GMM (Gül, 2008)) lies in the detailedness of the various bottom-up models included in this research project. By analyzing each energy sector specifically, applying the best suitable modeling tool, allows more detailed insights in challenges from climate change adaptation and mitigation. The integration of results from the sector specific energy demand models into EuroMM, allows the investigation of strategies for achieving sustainable energy systems. However, the difficulty in this approach lies in achieving consistency in parameters which are common to all models (e.g. CO_2 prices), as well as the allocation of emission permits for the various sectors if climate mitigation targets are considered. This issue was resolved by firstly integrating parameters from global models (e.g. GDP growth) in the bottom-up models as well as iterating the results found in the bottom-up models, to obtain stable solutions for the given boundaries (e.g. climate targets). In the following section, the driving parameters for the model analysis in EuroMM will be introduced further.

3.2. Scenario Development

Due to the existing interlinkage between energy supply and climate change, the transition towards more sustainable energy systems is of great interest. It is therefore necessary to explore possible technological pathways which allow to achieve such system. The analysis of different pathways, needs an understanding of possible long-term developments of energy demand and supply. However, since there is not one single optimal solution to achieve sustainable energy systems, scenario analyses are useful to investigate possible development pathways in respect to key future uncertainties. Below, some of the key factors for the energy system analysis are described, although they are not directly included in EuroMM. However, these parameters are underlying drivers for energy demand and

therefore important to develop the scenarios described in this disserta-
tion. It is noteworthy that the scenarios developed in the course of the
ADAM project do not necessarily follow projections used by the Intergov-
ernmental Panel of Climate Change (IPCC) which were presented in the
Special Report on Emission Scenarios (SRES) (Nakićenović et al., 2000).
However, the scenarios described here, based on the assumptions made
in the course of the ADAM project (Jochem et al., 2007), were assumed to
describe median scenarios for population growth and GDP development
in Europe.

3.2.1. Basic Scenario Drivers

One of the important drivers for energy demand trends in Europe is the
development of its future population. However, it is not only the num-
ber of persons living in Europe which drives energy demand but also
the social and demographic structure is important for projecting energy
demand. Additionally, the expected economic development is important
to derive estimates on the energy intensity of Europe. In the baseline
scenario described here, the estimates for the future European popula-
tion are based on Eurostat data for fertility and death rates. Depending
on these numbers the demographic development (e.g. age structure) is
calculated (Jochem et al., 2007, chp. 3), including assumptions on mi-
gration. The projections for population (a) and GDP (b) for Europe used
in the course of the ADAM project are given in figure 3.1.

Another important aspect of future energy scenarios is the cost of en-
ergy sources, i.e. coal, oil and gas. The cost for producing and delivering
energy carriers which are traded internationally was based on estimates
from the global model POLES (Jochem et al., 2007). For the baseline
scenario, the energy prices without taxes are given in figure 3.2.

Further assumptions were made regarding the availability of nuclear
power, renewable sources and emission taxes. In case of nuclear power,
countries with supporting policies for nuclear energy, are modeled with
a nuclear potential up to 2050 that is defined by the following estimate.
For each country, the number of on-line sites today is multiplied by a

(a) Population   (b) GDP
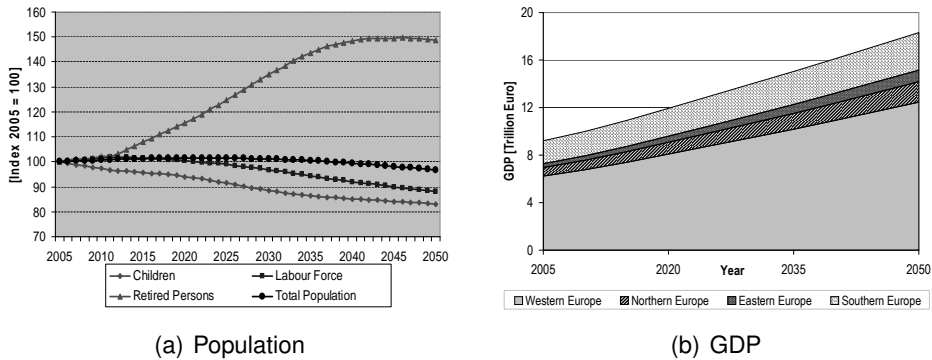
FIGURE 3.1.: *Estimates for population growth and related demographic parameters (a) and GDP estimates for all European countries aggregated to 4 major regions (b), the basic scenario drivers from Jochem et al. (2007).*

factor of 1.6, which is considered as a likely power plant size, expressed in GW of capacity, in the future. For instance, France, with a number of 58 sites today has therefore a nuclear potential of 92.8 GW installed which corresponds to a possible capacity increase of approximately 47% compared to 2005. The considered potential for renewable energies was based on estimates described in section 3.3.3 and with further details in table 3.1.

Additionally, a low CO_2 tax of \$10 is introduced for all regions across all time periods, corresponding to the given low level of European emission taxes in 2005.

3.2.2. Climate Change Scenarios

Climate Change Adaptation

Given the various challenges from climate change on the energy sector, scenario analyses were developed, to investigate such impacts as rising temperatures on the energy system. Based on the driving elements of the baseline scenario, additional parameters were considered, which describe the impacts of climate change on the energy conversion sector. Therefore, the two major sectors of energy demand and energy conver-
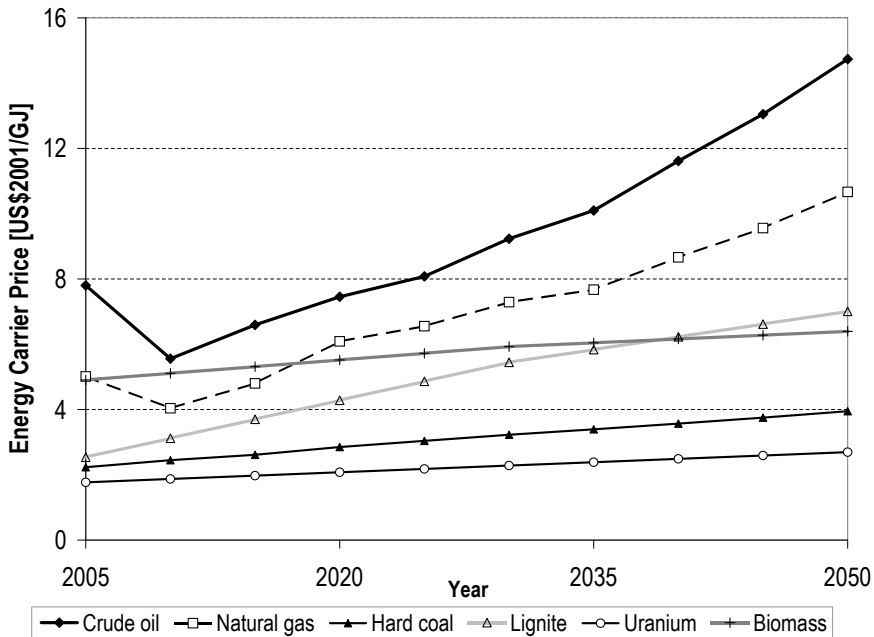
FIGURE 3.2.: *Prices for globally traded primary energy carriers in the baseline and adaptation scenario in US$2001 (Jochem et al., 2008). Biomass prices relate to an average feedstock price and are not intended to include refined biofuels.*

sion were analyzed for potential changes. In this section described here, only the impacts of climate change on the demand side are further introduced as drivers for the scenario analysis, since these changes were not explicitly modeled in the course of this dissertation. The impacts from climate change on the energy conversion sector are described in the following chapter 4.

Air temperatures and their increase due to climate change were used to estimate energy demand for space cooling and space heating in the residential and services sectors. Temperature estimates due to climate change were based on model calculations from Isaac and van Vuuren (2009). Rising temperatures change the number of cooling degree days and heating degree days which are commonly used to estimate energy

demand for heating and cooling purposes. Due to the changes in the above mentioned parameters, it is expected that the electricity demand in summers will increase since more floor area will be cooled by air conditioners. In winters, the demand for fuels and electricity for space heating is likely to decrease, due to a smaller difference between in-house and outside temperatures. In case of heated floor area, the main fuel used for heating in each country is influenced by national preferences for different heating systems, e.g. France has a high share of electric heating devices, while other countries like Germany or Switzerland rather use heating oil or natural gas in burners. In section 3.2.3, the changes in energy demand, based on changes in heating and cooling degree days for the adaptation scenario, are further outlined. The changes in heating degree days and cooling degree days due to climate change, based on Isaac and van Vuuren (2009), are given in figure 3.3, for selected European countries.

As a reminder to the reader, parameter assumptions from the baseline scenario, such as energy prices, GDP-growth and population growth remain unchanged in the adaptation scenario described here.

Climate Change Mitigation Scenarios

The baseline scenario drivers were also used to build the foundation of different climate change mitigation scenarios. However, two major changes to the model code were necessary, to deal with such scenarios. On the one hand, greenhouse gas emission reduction targets were introduced. In this analysis, model calculations were based on emission caps, which define a pathway, equivalent to stabilizing temperature increase at below 2 °C. For Europe, this emission cap was based on estimates from the global POLES model (Jochem et al., 2008; Schade et al., 2009). The emission cap only includes CO_2 emissions from the direct use of fossil fuels in the energy sectors and other GHGE were not included in this analyses. However, due to the uncertainties of staying below 2 °C temperature increase for a specific emission cap until 2100, two mitigation scenarios were considered in this dissertation. The first mitigation target was equivalent to reaching a threshold GHG concentration of 450 ppm CO_2-eq in

(a) Number of Heating Degree Days per Year

(b) Number of Cooling Degree Days per Year
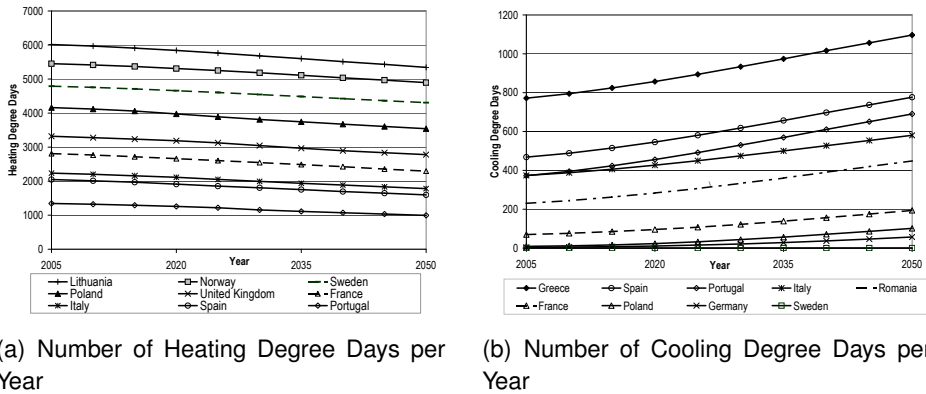
FIGURE 3.3.: *Estimates for the number of heating degree days (a) and cooling degree days (b) for selected European countries, scenario drivers in the adaptation scenario (Jochem et al., 2008).*

2100 on global level, which is afflicted with a probability of 50% of staying below 2 °C temperature increase. However, since the 50% probability is not considered as save enough to avoid serious damage to the Earth system, stronger emission reduction targets are likely to be necessary (Fisher et al., 2007). Given the uncertainty for climate change mitigation targets to stabilize temperature changes based on scientific bases, and the political interest in stronger climate targets (European Commission, 2007b), a second mitigation target was included in this scenario analysis. Therefore, an emission reduction pathway, equivalent to a 400 ppm CO_2-eq GHG concentration target for 2100 was analyzed. With this target, the probability of staying below 2 °C temperature increase, grew to 80%. For both mitigation scenarios, the according CO_2 emission targets are depicted in figure 3.4, (a).

Given the stringent emission targets, it is expected that fossil energy carriers are likely to play a smaller role in the energy system. Therefore, the pressure on depleting fossil resources such as oil and natural gas will decrease, leading to lower energy carrier prices (figure 3.4, (b)).
Both climate mitigation scenarios are further described in more detail in chapter 5.

(a) Emission Targets

(b) Energy Prices
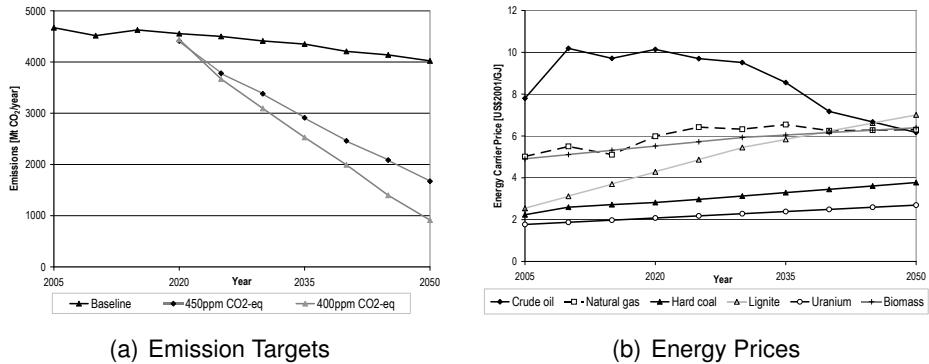
FIGURE 3.4.: *Estimates for different CO_2 emission targets for achieving green-house gas concentrations of 450 ppm CO_2-eq and 400 ppm CO_2-eq, respectively, compared to the emission results for the baseline scenario (a). Figure (b) shows the energy carrier prices for the 450 ppm CO_2-eq scenario, used for the mitigation scenarios, based on Schade et al. (2009).*

3.2.3. Energy Demands

Based on the different scenario drives described earlier (fuel prices, GDP-changes), final energy demands were estimated from demand specific bottom-up models within the ADAM project (Jochem et al., 2007, 2008; Schade et al., 2009). The estimates for final energy demand for the different scenarios were used as input to EuroMM. Slight differences in the total amount of final energy demand between EuroMM and the data described in Jochem et al. (2007, 2008); Schade et al. (2009) were based on different model calibration years. As mentioned in section 3.3.2, EuroMM was calibrated to the year 2005. Other models within the ADAM consortium used different calibration years (e.g. year 2000). Therefore, the demand growth rate from the different bottom-up models was used to forecast future final energy demand in EuroMM, rather than the actual output values. All demand projections were obtained as energy carrier demand, i.e. demand for coal, gas, oil, oil products, biomass and electricity, for the industrial sector, the transport sector, the services (including agriculture) and residential sector. The electricity demand for the residen-

tial and services sector was further disaggregated in season specific demands (e.g. electricity for space heating and cooling), and non-seasonal electricity demand (e.g. electrical appliances). An overview of the final energy demand projections for the different scenarios is shown in figure 3.5.

3.2.4. Further Scenarios

Based on the mitigation scenarios described above, further scenarios were developed to investigate different uncertainties in model assumptions regarding technological and policy constraints to the energy system in Europe. On the one hand, it is not sure that all technologies which are available today, or which are expected to be available in the future, will contribute to electricity generation as projected in the mitigation scenarios. Therefore, different constraints were introduced in the analysis in various steps, to analyze the potentials of wind power technologies, the influence of different nuclear policies in Europe and uncertainties in the availability of fossil electricity generation technologies equipped with carbon capture and sequestration (CCS).

Additionally, the issue of decreasing electricity demand under climate change mitigation scenarios was addressed. Given the high efficiency increase of final energy demand in the residential and services sectors (Schade et al., 2009, chp. 6), it remained uncertain if these efficiency improvements could be realized. Therefore, the mitigation scenarios and the further scenarios analyzing uncertainties of model assumptions were additionally investigated under the assumption of higher electricity demand. To do so, the given electricity demand projections for the two mitigation scenarios were increased by approximately 1% per year, leading to scenarios with an overall increase in electricity demand from the residential and services sector of approximately 50% until 2050, compared to the scenarios where high efficiency gains were assumed.

(a) Baseline Scenario

(b) Adaptation Scenario

(c) 450 ppm CO$_2$-eq Scenario

(d) 400 ppm CO$_2$-eq Scenario
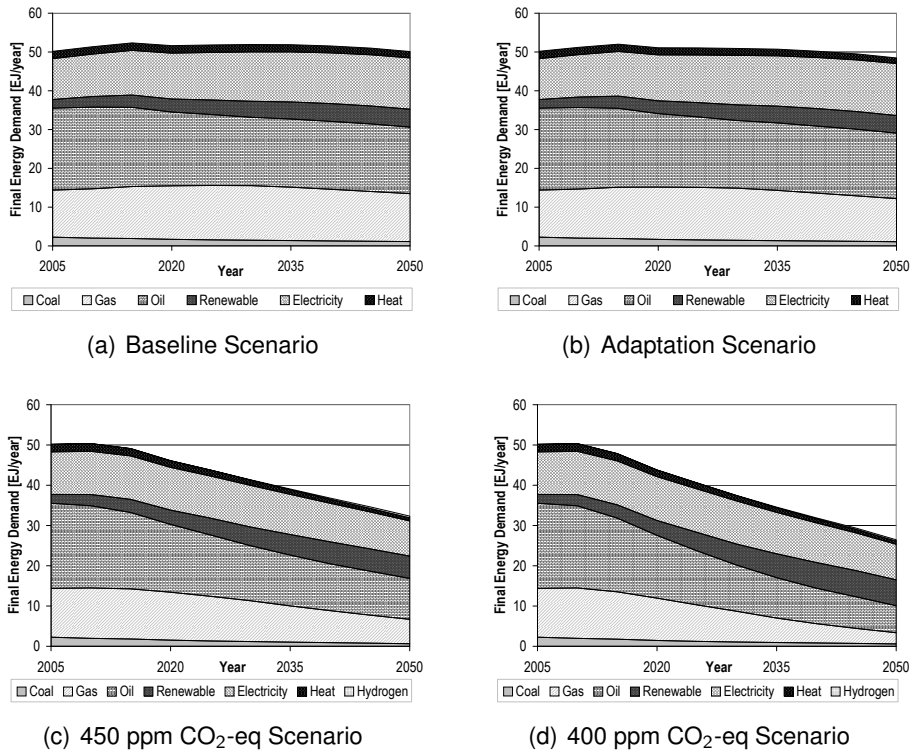
FIGURE 3.5.: *Final energy demand for the four different scenarios, and for various energy carriers introduced in section 3.2, based on the ADAM project outline.*

3.3. EuroMM - the European Energy Conversion Model

EuroMM was developed in the course of this dissertation at the Paul Scherrer Institute, in context of the European ADAM project, where it was used to analyze climate change adaptation and mitigation scenarios for the European energy conversion sector. EuroMM included features in the electricity sector such as a detailed representation of electricity generation technologies, the electricity grid infrastructure including a detailed representation of electricity trade flows between European countries and country aggregations, as well as seasonal electricity demand patterns

and load curves, for some of the electricity generation technologies.

Technically, EuroMM is a bottom-up, perfect-foresight optimization model which is part of the MARKAL (MARKet ALlocation) family of models which represent current and potential future energy technologies (Loulou et al., 2004). This kind of model is typically used to determine the least-cost energy system configuration for a given time horizon, under a set of assumptions about technologies, resource potentials and energy demand. Perfect foresight refers to the fact that the model operates under the assumption of a single, global social planner that is able to "foresee" the future and take optimal decisions in each time period that will lead to a least-cost energy system for the whole time horizon.
That is, the model provides an indication of what is the optimal outcome for the energy system under a given set of constraints, rather than a prediction. Therefore, the EuroMM model can be used to compute the impact of policy instruments or the internalization of externalities, on selected indicators such as costs, emissions, etc. In this dissertation, the model is used to investigate energy sector specific policies, such as CO_2 emission caps, as well as technology specific constraints on the future use of electricity generation technologies. To do so, EuroMM provides a detailed representation of energy supply technologies in the electricity and fuel conversion sectors.

The foundation of the MARKAL modeling approach is the so-called Reference Energy System (RES), which is illustrated for EuroMM in figure 3.6. The RES is a representation of currently available and possible future energy resources, technologies and energy carriers. From the options available in the RES, the MARKAL model chooses the least-cost energy system and energy flows for a given time horizon and energy demands.

The optimization problems described in the scenarios in this dissertation were solved via mixed integer programming (MIP). This was a non linear approach to the specific research questions, by forcing the model to invest in integer multiples of a certain technology, given a pre-defined capacity block size (also called lump size). This is, if the model invested
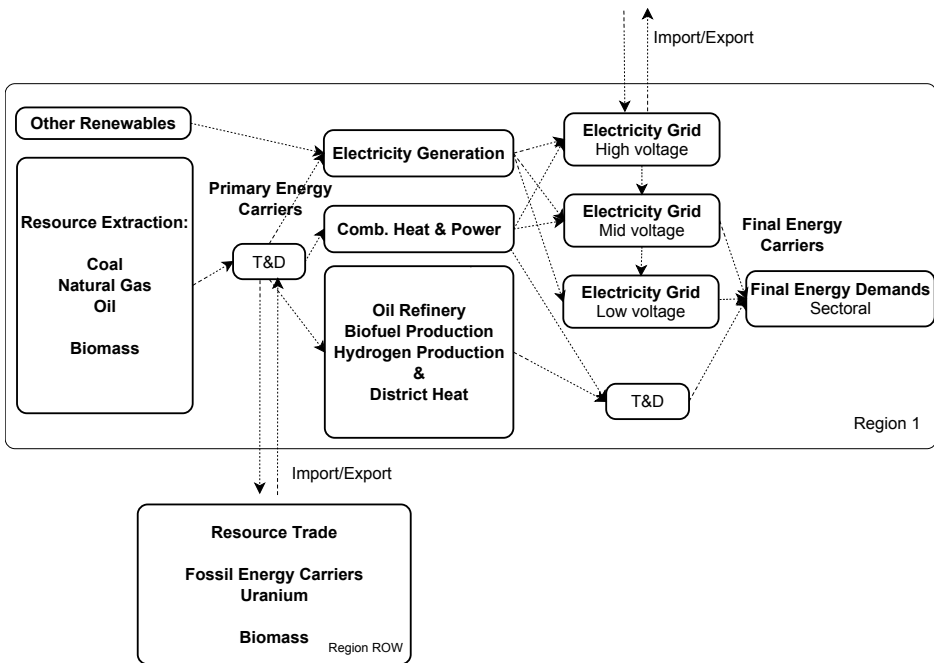
FIGURE 3.6.: *Stylized reference energy system, as it was implemented in Eu-*
roMM. The RES described for Region 1 in this figure was implemented
in all 18 regions in EuroMM. Imports and exports of electricity were de-
fined for all neighboring countries of Europe. The region ROW (rest of
the world) included all resource potentials from outside of Europe.

in a large scale technology (e.g. coal fired power plant), a multiple integer
of a certain block size (e.g. 500 MW) needed to be installed. Fractions of
this block size were not available for the model to invest in.

   This approach was used to depict differences in the use of large scale
technologies, compared to small scale technologies, which was espe-
cially important for the introduction of new technologies into the energy
system. Due to the economy of scales (Gowing, 1974), investments in
large scale technologies are usually favored in terms of cost, compared to
smaller scale technologies. However, if for example only a small demand
for a specific energy carrier needs to be covered, it is more efficient to
install a small unit of a costlier technology in relative terms as compared

to the installation of a large unit of a relatively cheaper technology.

Given the characteristics of the MIP approach, a maximum relative gap between the optimal solution and the integer solution of the problem was set to below 0.015%. This gap width between optimal and integer solution can be chosen by the modeler, and reflects the balance between accuracy of the solution and computation power for finding the specific solution.

In the following of this section, EuroMM is introduced in more detail, describing the above mentioned special features as well as general assumptions, made in the development of the analysis, which made the model suitable for the investigation of climate change adaptation and mitigation challenges in the energy sector.

3.3.1. Regional Disaggregation

To describe the European energy sector in detail, EuroMM disaggregates Europe (i.e., EU-27 plus Norway and Switzerland) into 18 regions (see figure 3.7 for regions and their acronyms). This set-up was chosen to describe the energy system of large European countries, such as France or Germany, with different historically grown infrastructures, as non aggregated regions. Due to a software related limitation, smaller countries such as the Baltic countries, or groups of countries with only one grid connection to neighboring regions (e.g. Portugal and Spain to France or Ireland and UK to France) were aggregated for not exceeding the maximal number of 18 regions allowed.

3.3.2. Model Calibration

The model was calibrated to the statistical values of the year 2005, using Eurostat and ENTSOE data (ENTSOE, 2005; Eurostat, 2005) for electricity generation and demand. In case of data gaps (e.g. resource availability or installed capacities for electricity generation), additional information was taken from IEA and the WEC (IEA, 2004*a*; WEC, 2004). The model described scenarios until the year 2050 using 5-year time steps. Each time period is subdivided in 3 seasons (summer, winter, intermediate)

Acronym	Countries
AUT	Austria
BAL	Estonia, Latvia, Lithuania
BELU	Belgium, Luxembourg
BURO	Bulgaria, Romania
CZSL	Czech Rep., Slovak Rep.
FR	France
GBI	United Kingdom, Ireland
HUSLE	Hungary, Slovenia
IBE	Portugal, Spain
ITA	Italy
MC	Cyprus, Malta
NOR	Norway
POL	Poland
SCA	Denmark, Finland, Sweden
SWI	Switzerland
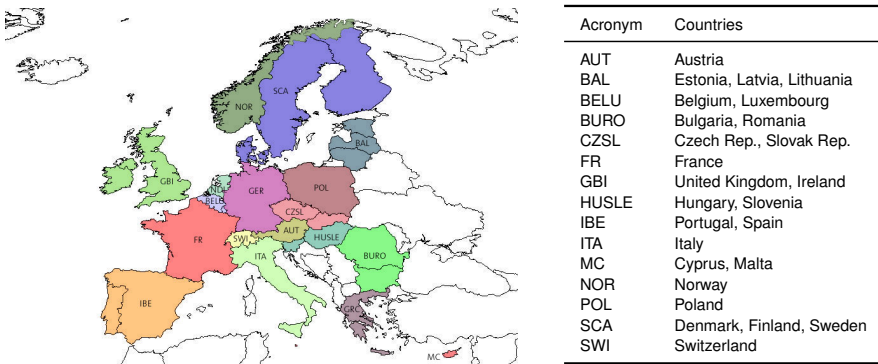
FIGURE 3.7.: *Disaggregation of Europe into 18 regions which were considered in EuroMM. The number of allowed regions within MARKAL-models is limited to 18, for software specific reasons.*

with day and night time slices uniform across all regions.

3.3.3. Resources and Costs

The analysis of potentials for fossil energy carriers (resources and reserves) was based on studies from the WEC (WEC, 2004), and estimates from Enerdata (Enerdata, 2005). Since this study focused on Europe, the import of fossil energy carriers to Europe from the rest of the world was not limited by competition with other world regions. In this model, the cost for fossil energy carriers was split up into a cost for mining, a cost for transporting the fuel to the importing region, and transportation costs within a region. By this set up, the model favors resources, which were available within a region, since the total cost for each fossil energy carrier could be reduced by the cost for transporting the energy carrier from the ROW to the regions in Europe. This was due to the assumption that fossil based power plants are located near the domestic resource locations in Europe and therefore the more expensive transport of energy carriers from the mining area to the power plants could be avoided. In total, the cost for importing fossil energy carriers matches the international prices derived from the POLES model (Jochem et al., 2007, chap. 4) in the baseline and adaptation scenario. In the mitigation scenarios, the cost for fossil energy carriers such as crude oil and natural gas was lower,

due to reduced demand and the switch to other energy sources (Schade et al., 2009, chap. 4).

In this dissertation, the potentials for renewable energy from wind, solar and geothermal sources were adapted from Jochem et al. (2007) and can be found in table 3.1. The European biomass potential given in table 3.1 included all types of biomass such as stover, wood residues, and energy crops for electricity generation and biofuel production, and was based on a study from Ericsson and Nilsson (2006). In the case of biomass imports, no limitations were implemented for countries to import biomass feedstock for biofuel and electricity production. However, the option of importing and trading refined biofuels was not available in the model.

All primary energy carriers were traded bilateral between the region ROW and the different regions implemented in EuroMM. There was no bilateral trade of primary energy carriers between European regions.

3.3.4. Characteristics of the Energy Conversion Sector

Electricity and Heat Generation Technologies

The technologies generating electricity and/or heat as described in table 3.2 were included in the model. Each technology was defined by its associated costs (investment cost, fixed operation and maintenance cost and variable operation and maintenance cost), efficiencies, load factors, and installed capacities in the calibration year (see table C.1 in the appendix for an overview of the implemented parameter assumptions). In addition, CCS has been considered for some of the technologies. For hydro power plants, solar photovoltaics, solar thermal power plants as well as wind turbines, a differentiation of sizes (e.g. large hydro, small hydro), location (e.g. wind off-shore, wind on-shore) and availability was integrated in the model. Additional to the use of annual availability factors described in table 3.2 for most of the technologies, hydro power plants and wind turbines were modeled differently. In the case of hydro power, the seasonal reservoir availability was defined, which allows to express the influence of climate sensitive parameters such as river runoff on power generation. For wind turbines (onshore and offshore) 5 different cost steps were im-

TABLE 3.1.: *Resource potentials for fossil energy carriers, as well as renewable potentials in Europe. Biomass includes estimates for stover, wood residues, crops and wastes. The potential for wind power and solar power were adapted from estimates described in Reiter et al. (submitted).*

	Hard Coal [EJ]	Lignite [EJ]	Natural Gas [EJ]	Crude Oil [EJ]	Biomass [PJ/yr]	Wind [TWh/yr]	Solar [TWh/yr]
AUT	0	1	1	0	513	9	1
BAL	0	66	0	0	966	14	0
BELU	0	0	0	0	113	17	2
BURO	30	148	11	6	1658	20	0
CZSL	169	9	1	0	831	29	9
FR	3	0	0	1	4048	224	33
GBI	28	14	29	24	1834	216	0
GER	674	1208	7	2	986	163	62
GRC	0	81	0	0	416	23	16
HUSLE	46	81	1	1	674	3	1
IBE	17	3	0	1	2037	185	47
ITA	1	0	5	4	578	54	46
MC	0	0	0	0	13	2	1
NDL	14	0	55	1	231	45	0
NOR	0	0	143	47	117	76	0
POL	340	62	4	1	3314	42	0
SCA	0	0	4	8	1391	101	1
SWI	0	0	0	0	501	0.1	0
EU-27+2	1322	1672	261	96	20219	1224	220

plemented (based on data obtained from the PowerACE model (Reiter et al., submitted)), describing different full load hours for capacity installations of less favorable wind locations within each region. Therefore, the assumed wind power potential was split over the modeled time horizon, considering that less favorable wind conditions would increase the cost of installed capacity.

For some of the technologies given in table 3.2, a fixed capacity lump size was defined to force the model to invest either in an integer multiple of the given capacity or not to invest at all in the specific technology. In EuroMM, large scale technologies using natural gas had a fixed capacity size of 300 MW, coal fired power plants were fixed to 500 MW, and

nuclear power plants had a lump size of 800 MW. All other technologies were not limited by a certain lump size.

Carbon Capture Technologies

The energy-conversion EuroMM model incorporated CCS in electricity generation and hydrogen production technologies. For CCS in the electricity generation sector, separate capture technologies were incorporated for advanced coal power plants (post-combustion), CO_2 capture in natural gas power plants (post-combustion), and CO_2 capture in coal integrated gasification combined-cycle (IGCC) power plants (pre-combustion). Performance parameters for the different CCS technologies in electricity generation were based on a study from IEA (2004*b*) and are given in table C.2. In addition, CO_2 capture in hydrogen production facilities using natural gas steam reforming and coal gasification technologies had been incorporated based on data derived from Gül (2008).

Power Generation and Transmission

For the energy conversion sector, the year was divided into six time-divisions (time-slices). The model allowed then the representation of load duration curves for electricity- and heat demand, distinguishing seasonal (winter, summer, intermediate) and daily (day, night) load patterns. The demand for electricity was calculated for each season (winter, intermediate, summer) and time-of-day (day, night). To cope with the load profile, the set of electricity generation technologies was divided into subsets, which have different roles in the model. For instance, power plants designated as base load plants, were constrained to operate at the same rate day and night in the same season, while other plants were specified as peak plants. Centralized and decentralized power plants were distinguished. The electricity and heat generation was linked via a transmission and distribution grid with final energy demand sectors. The electricity grid was divided into 3 voltage levels (high voltage, medium voltage and low voltage), including losses on the high and medium voltage grid, which were used by centralized power plants for electricity transmission. No transmission and distribution losses were included in the low voltage grid.

TABLE 3.2.: *List of technologies describing the electricity and heat generation sector in EuroMM. The technologies are split in specific categories. See table C.1 in the appendix for an overview of related performance assumptions. CHP stands for combined heat and power systems.*

Category	Technology	Acronym
Fossil Generation	Coal-powered Conventional Thermal	E01
	Pressurized Coal Supercritical	E02
	Lignite-powered Conventional Thermal	E03
	Gas-powered Gas Turbine in Combined Cycle (GTCC)	E11
	Gas-powered Turbine	E12
	Gas-powered Conventional Thermal	E13
	Integrated Coal Gasification with Combined Cycle (IGCC)	EIG
	Oil-powered Conventional Thermal	E70
	Oil-powered Gas Turbine in Combined Cycle	EIO
CHP Fossil, Conventional	Gas Combined Cycle Condensing, CHP	E6A
	Gas Combined Cycle Backpressure, CHP	E6A1
	Coal Steam Turbine Condensing, CHP	E6C
	Coal Steam Turbine Backpressure, CHP	E6C1
	Oil Internal Combustion, CHP	E6D
Fossil with CCS	Coal IGCC with CCS	EIC
	Pressurized Coal Supercritical with CCS	EC2
	Gas-powered Gas Turbine in Combined Cycle with CCS	E1C
Nuclear Generation	Conventional Light-Water Nuclear Reactor	E21
	New Nuclear Design	E22
Renewable Generation	Conventional, large-size Hydro Power	E31
	Small Hydro Power (¡10 MWe)	E32
	Decentralized PV Systems with Network Connection	E41
	Solar Thermal Electric	E42
	Onshore Wind Power	E61
	Offshore Wind Power	E62
	Biomass Gasification with Gas Turbine	E82
	Biomass Direct Combustion	E84
	Bio-waste Gasification with Gas Turbine	BWA
	Geothermal Electricity	GEO
CHP Renewable	Biomass steam turbine condensing	E6B
	Integrated Biomass Gasification with Combined Cycle	E6B1
	Biogas Internal Combustion	E6E
CHP Fuel Cells	Gas Powered Fuel Cell (MCFC), CHP	E15
	Gas Powered Fuel Cell (SOFC), CHP	E16
	Biogas Powered Fuel Cell (MCFC), CHP	E17
	Biogas Powered Fuel Cell (SOFC), CHP	E18
	Hydrogen Powered Fuel Cell (SOFC), CHP	EH4
District Heat	Fossil Fuel Based Heat Plants	DHE6A,-C,-D
	Renewables Based Heat Plants	DHE6B,-E

The electricity grid was defined by a simplified capacity for the electricity transmission and distribution network, independent of the actual grid length, which was necessary to link electricity generation and demand. In case of installation of new grid capacity for trade reasons, the necessary investments were calculated for an average connection of 200 km length per GW of electricity trade. Investment costs were defined for four different types of grid connections (e.g. mountainous regions or highly populated regions need higher investments compared to less populated regions), based on a literature review (CESI et al., 2005; ICF, 2002).

Trade of Electricity

The electricity trade was represented by bilateral trade flows between pairs of contiguous regions in EuroMM, on the level of the high voltage electricity grid. Trade flows were allowed for all six time divisions and no bounds were included for specifying certain trade patterns, which were in place in the year 2005. By allowing for bilateral trade, the model was able to minimize the cost function by balancing electricity generation within a region and possible bilateral trade with neighboring regions. This was important for certain cases in this analysis, where technologies were not available within one region due to policy constraints or limited potentials, while by including trade, this form of electricity could be imported from the neighboring region. For the time being, no electricity trade was assumed between Europe and regions outside the boundaries of the model (e.g. with Russia, Ukraine or North Africa). In the future, the possibility of representing electricity trade from North Africa directly in the model is considered.

Fuel Production

In the following, fuel production technologies incorporated into the energy-conversion EuroMM model are introduced. EuroMM included modules for biofuel and hydrogen production based on the findings from Gül (2008). In addition, fuel transformation (liquefied natural gas and compressed natural gas) as well as fuel transmission and distribution was considered in the model.

For all regions within the model separate oil refineries were modeled. All relevant fuel types such as gasoline, diesel, jet fuel, LPG, naphtha, heavy fuel oil, refinery gas and other oil products were available as output from the refineries. The initial share of each fuel type as output of the refinery was based on values from Eurostat (Eurostat, 2005). However, the output shares of the refineries in the model were not fixed over time, rather flexible output shares were set by limiting the maximum share of each fuel represented by the technical possibilities of refineries. In the model, all petroleum-based fuel types can be traded internationally with the rest of the world outside EU27+2. No bilateral trade between neighboring countries for fossil fuel products was considered in EuroMM.

EuroMM also included a detailed module for biofuel production which comprised the technologies described in table 3.3. These technologies with associated costs and efficiency parameters were described in Gül (2008) in more detail. The model chooses the cost optimal production of biofuels, to cover biofuel demand from final energy demand sectors.

TABLE 3.3.: *List of technologies included in the Biofuel module.*

Feedstock	Technology
Wood	Biodiesel by Pyrolysis
	FT-Diesel by Gasification
	DME by Gasification
	SNG by Gasification
	Methanol by Gasification
Oil crops	FAEE by Esterification
Domestic Waste	SNG by Anaerobic processes
Corn	Ethanol
Sugar Crops	Ethanol
Cellulosic Biomass / Stover	Ethanol

EuroMM also included a hydrogen module based on Gül (2008), with a detailed representation of hydrogen production, transport and distribution technologies. Main hydrogen production technologies were hydrogen from wind (electrolysis), hydrogen from fossil sources and hydrogen based on nuclear fuels, implemented as centralized production technologies. Additionally, hydrogen was also available from decentral production technologies based on e.g. fuel reforming and electrolysis. Hydrogen transport was also included, but no trade of H_2 was available between modeled regions.

As a further module, EuroMM described other energy conversion sectors, such as coke production from coal and lignite, derived gas production from coal, lignite and coke as well as briquette production from lignite. Main sources for data regarding cost parameters and efficiencies were derived from Amendola (1999); Eurostat (2005); Johansson and Holappa (2004). However, synthetic fuels from fossil based technologies, such as coal-to-liquids were not included in EuroMM.

Prices for Secondary Energy Carriers

The prices for electricity and other secondary energy carriers, such as hydrogen and biofuels were endogenous to the model. Prices were generated as the marginal costs of the fuel related constraint balancing between demand and supply. The electricity marginal prices reacted to the imposition of related policy instruments, such as constraints on CO_2 emission levels, and CO_2 taxes. That is, under a CO_2 constraint, electricity prices would normally become higher, as the electricity technology mix is decarbonized, requiring installation of generally more expensive low- or zero-emission technologies. The CO_2 price was generated in the model as the marginal cost of the corresponding constraint. The model included trade of electricity with specified transaction costs. The prices for other secondary energy carriers were only indirectly linked to the CO_2 constraint since demand for fuels such as hydrogen or biofuel were exogenous to the model.

3.4. Baseline Scenario and Results

In this scenario, a business-as-usual development of the energy system was considered. In this case, the main influences on the energy system include economic and demographic drivers of demand, and policies already in place in European countries in 2005. Therefore, EU-wide targets, such as the 20-20 renewables goal, and the biofuels directive were excluded from the baseline, but the continuation of national energy policies (e.g. nuclear policies and abatement policies equivalent to a low CO_2 tax of $10 over the model horizon) was assumed and accounted for, but no further emission reduction targets or climate change adaptation measures were incorporated. An overview of the main input assumptions for the baseline scenario is given in table 3.4.

3.4.1. Electricity Generation and Primary Energy Supply

Under the baseline scenario, the total gross electricity generation in Europe (EU27+2) increased in line with the demand assumptions, and was estimated to grow by approximately 19% until 2050, from approximately 3,600 TWh to approximately 4,200 TWh (see figure 3.8, (a)). The dominating fuel source for electricity generation in Europe until 2050 in this scenario was coal (mainly hard coal but also lignite in some regions), which increased its share from 27% in 2005 to 31% in 2050. Besides the conventional lignite thermal generation capacity (64 GW installed in 2050), mainly pressurized coal supercritical capacity (113 GW in 2050) was found for coal based power generation. Natural gas only played a minor role at the end of the model horizon due to the high gas price and the depletion of European gas reserves. This reduced the contribution of gas-fired electricity generation from 22% in 2005, to less than 5% in 2050, although gas continued to playing an important role for thermal uses (figure 3.8, (a) and (b)).

Nuclear power preserved its contribution to electricity generation on a comparatively constant level, amounting to approximately 26%, which is equal to 1220 TWh in 2050. Electricity generation from renewable sources increased its share from 18% to 31% in 2050, mainly due to

TABLE 3.4.: *Overview of the main input assumptions to the model EuroMM for the baseline scenario. The exogenous input parameters (marked with *) were obtained from partners of the European ADAM project (Jochem et al., 2007).*

Scenario-drivers baseline	Additional information
Energy demand*	Relatively stable demand for all final energy carriers until 2050
Fuel prices*	Oil price 180% of 2005, other fuels between 125% (biomass) up to 270% (lignite) of 2005 prices
Technology assumptions*	Cost, availability, efficiency
CO_2-tax	$10 per ton of CO_2
Nuclear policies	Country specific (e.g. nuclear phase-out in Germany and Sweden)
Population growth*	Decline of -0.1% per year until 2050. Indirectly applied in EuroMM via final energy demand assumptions
GDP-growth*	Average increase by 1.5% per year until 2050. Indirectly applied in EuroMM via final energy demand assumptions

the increase of wind power generation which was found to be cost competitive to other conventional generation technologies. Other renewable technologies (biomass and solar based electricity generation) only contributed by a small share (less than 5%) to total generation.

The total primary energy supply (TPES) remained almost constant (see figure 3.8, (b)) until 2050, compared to the calibration year 2005. Fossil fuels are expected to continue to be the dominant energy resource for providing energy services. Up to 70% of primary energy would be based on coal, oil and natural gas. Oil was used in the transportation sector as well as for heating pruposes in the residential sector. Natural gas was used for electricity generation to a large extent only in the first periods of the model horizon and was additionally used for heating purposes in the residential and services sector. Nuclear sources increased their share in

(a) Electricity Generation   (b) Primary Energy Supply
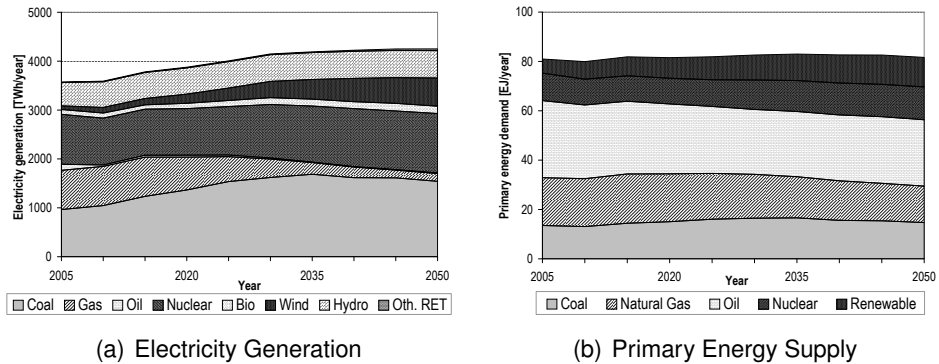
FIGURE 3.8.: *Electricity generation in the baseline scenario under the given set of assumptions (a) and primary energy supply (b) for EU27+2.*

primary energy supply from 13% to 16%, and renewable sources doubled their contribution in primary energy supply from 7% to 14%.

Due to the old infrastructure for electricity generation in Europe (Kjärstad and Johnsson, 2007*a*) which needs to be replaced in the coming decades and the growing demand for electricity, large investments are needed to install sufficient generation capacity up to 2050. The according cumulative investments needed are shown in figure 3.9. Additionally, investments are needed to provide alternative fuels, such as biofuels, covering a demand for biodiesel and ethanol of up to 1 EJ in 2050. It is expected that approximately $1.6 trillion would be needed in the energy conversion sector until 2050. The large share of investments in hydro power generation was based on the assumptions on reinforcing existing capacity, rather than investments in new generation capacity.

The cumulative discounted system costs in Europe were estimated to approximately $4.2 trillion until 2050, including technology investments, fixed and variable operation and maintenance costs as well as domestic fuel extraction and transaction costs for fuel imports within EU27+2. However, the cost of fuels imported, need to be accounted for as well. Such discounted cumulative fuel cost were in the range of $6.5 trillion
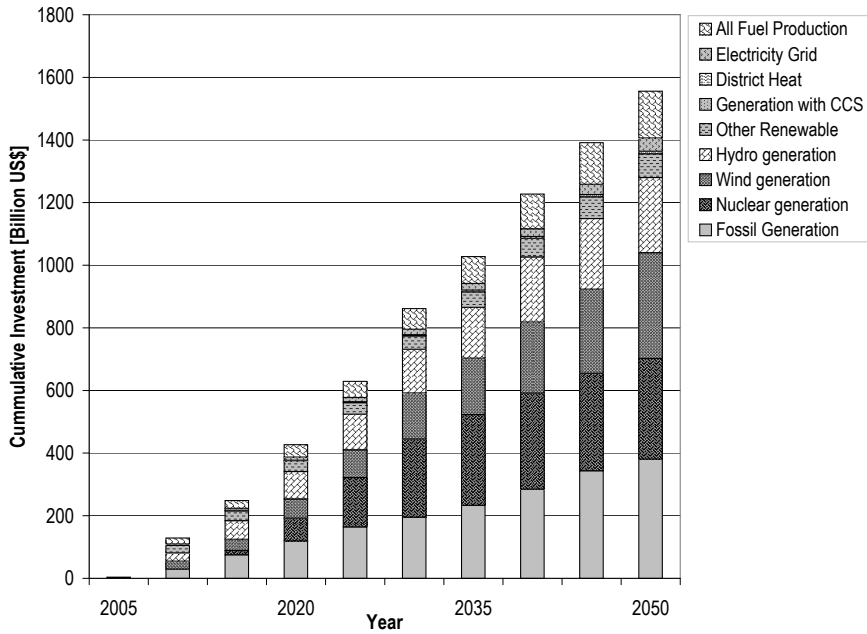
FIGURE 3.9.: *Total cumulative undiscounted investment costs needed in the electricity generation sector up to 2050 in the baseline scenario.*

until 2050. Therefore, the total cumulative discounted system cost was in the range of $10.7 trillion until 2050.

4. Climate Change Adaptation

4.1. Introduction

The impacts of climate change on the energy conversion sector are often mentioned in climate science (see for example Parry (2000) for further discussion), but to my knowledge no quantitative analysis has been conducted so far to estimate impacts and related costs on European level. However, these impacts are various and could pose a serious pressure on the energy infrastructure in terms of energy supply and demand. For instance, it remains open how the seasonal energy demand will change due to rising temperatures and which are the implications on e.g. electricity generation, to provide sufficient energy for the demand sectors. Climate change affects European regions differently, and therefore the necessary adaptation measures are likely to vary across Europe.

In this dissertation, a first approach to quantify adaptation measures in the European energy conversion sector is undertaken, using the cost optimization model EuroMM. This chapter explores the impacts of climate change on the European energy conversion sector in absence of mitigation efforts applied after the year 2005. This analysis takes into account climate change induced impacts on the use of hydro power, on cooling capacities of rivers for thermal electricity generation, together with changes of energy demand.

The following chapter is organized as follows: in the sections 4.2, 4.3, 4.4 and 4.5, the climate change impacts are further introduced and analyzed for their potential influence on cost and efficiency of electricity generation technologies. A short review of the basic assumptions for the adaptation scenario is given in section 4.6. The results of the model analysis are presented, followed by a discussion and conclusions.

4.2. Climate Change Impacts on River Temperature

One of the main impacts regarding the energy sector due to climate change is the increase in average river temperatures. This temperature increase is of relevance because huge amounts of water are used in the energy sector for cooling purposes. According to Vassolo and Döll (2005), 121 billion m^3 of water were withdrawn in Europe in 1995 for energy purposes and approximately 4 billion m^3 were evaporated. By feeding back the withdrawn waters with higher temperatures into rivers, power plants are using the relatively cool rivers as heat sinks. However, there are environmental regulations which are limiting the allowance of temperature release into rivers. In the European freshwater directive (European Council, 2006), 2 different temperature parameters ΔT and T_{max} are defined (see table 4.1). ΔT describes the maximal allowed temperature difference between the river temperature before the zone of water withdrawal and the river temperature at the end of the mixing zone where the released cooling water has fully mixed with the undisturbed river. At the end of the mixing zone the river temperature should not exceed T_{max}. Additional, the European Directive 75/440/EEC (European Council, 1975) defines temperature thresholds of 22 °C and 25 °C as guiding and mandatory, respectively, for rivers which are intended for the abstraction of drinking water. Given these regulations, river temperatures are measured in the relevant zones in weekly periods to guarantee the compliance with the given standards.

Thus, it is of high interest how river temperatures will develop in the future in respect to climate change. With increasing air and river temperatures, shortfalls in electricity generation are possible. In other terms, if average river temperatures reach values at the level of the threshold temperature, utilities will be unable to release the maximum of cooling water for full load and hence will have to decrease the power output.

To estimate the impact of climate change on European rivers, different linear regression models were set up (Ullmann, 2008, Bachelor Thesis), based on the findings of Webb (1992), Pilgrim et al. (1998) and Erickson and Stefan (2000), to model changes in river temperature, depending on ambient air temperature and the geographical location of rivers. The as-

TABLE 4.1.: *Temperature thresholds as defined in the European Freshwater Directive for the release of heat into rivers (European Council, 2006). The definitions of salmonid and cyprinid refer to different fish species which need different environmental conditions for living.*

Parameter	Salmonid Waters	Cyprinid Waters
ΔT (°C)	Temperature measured downstream of a point of thermal discharge (at the edge of the mixing zone) must not exceed the unaffected temperature by more than:	
	1.5°C	3.0 °C
	Derogations limited in geographical scope may be decided by Member States in particular conditions if the competent authority can prove that there are no harmful consequences for the balanced development of the fish population	
T_{max} (°C)	Thermal discharges must not cause the temperature downstream of the point of thermal discharge (at the edge of the mixing zone) to exceed the following:	
	21.5°C	28.0 °C
	10.0°C	10.0 °C
	The 10 °C temperature limit applies only to breeding periods of species which need cold water for reproduction and only to waters which may contain such species.	

sumptions on changes in monthly average air temperature due to climate change were extracted from van Vuuren et al. (2006), with a data resolution on country level for monthly changes (see Appendix B.1).

In the study of Ullmann (2008, Bachelor Thesis), depending on the geographical region, the results vary in terms of importance regarding the temperature thresholds relevant for cooling of power plants. In Nordic regions, the estimated average river temperatures do not reach temperatures higher than 22 °C in average (see figure 4.1), and therefore no power output decrease is expected in summers. However, under site

specific conditions, maximum temperatures could reach values above 22 °C, which is of relevance for salmonid rivers used for cooling purposes. Additionally, the shift to higher temperatures earlier in the year might need to be considered in respect of the 10°C threshold. Due to the lack of data about spawning periods of fishes, possible limitations to power generation are not considered in this study for the 10 °C threshold. For all rivers site specific characteristics such as stream shading by vegetation, reservoirs, or the inflow of groundwater or artificial sources can influence temperature estimates. However, given a R^2-value (coefficient of determination) of 0.92 for the monthly regression analysis, the estimates are considered as accurate for the purpose of this study.

For more southern regions such as Hungary and Slovenia (HUSLE), the average temperatures are expected to reach values above 22 °C in summers, and therefore reductions in power output may be expected (see figure 4.2). Under extreme conditions depending on the characteristics of rivers, temperature levels of above 28 °C are also likely.

For the most southern countries of Europe, even higher river temperatures are likely to occur. Monthly average river temperatures were estimated to reach values of up to 27 °C in summer months in 2050, with a given standard deviation of 5.77 °C (see figure 4.3). However, according to Erickson and Stefan (2000), by using higher air temperatures as 25 °C to 30 °C for the regression estimates, the water temperatures are likely to be overestimated. They are suggesting an upper limit of 25 °C for a regression analysis, since the linear relationship between air temperature and river temperature seems to level off. In the analysis of Ullmann (2008, Bachelor Thesis), air temperatures of 25.8 °C were used as maximum in 2050 for Greece, but the water temperature estimates were considered as accurate for the purpose of this PhD study.

Due to a lack of data for the differentiation between power plants located at salmonid or cyprinid rivers, a temperature threshold of 25°C was chosen for all regions, to define the years and seasons from which on a decrease of water availability for cooling purposes can be expected. If the threshold temperature in a region is met, the availability of power plants
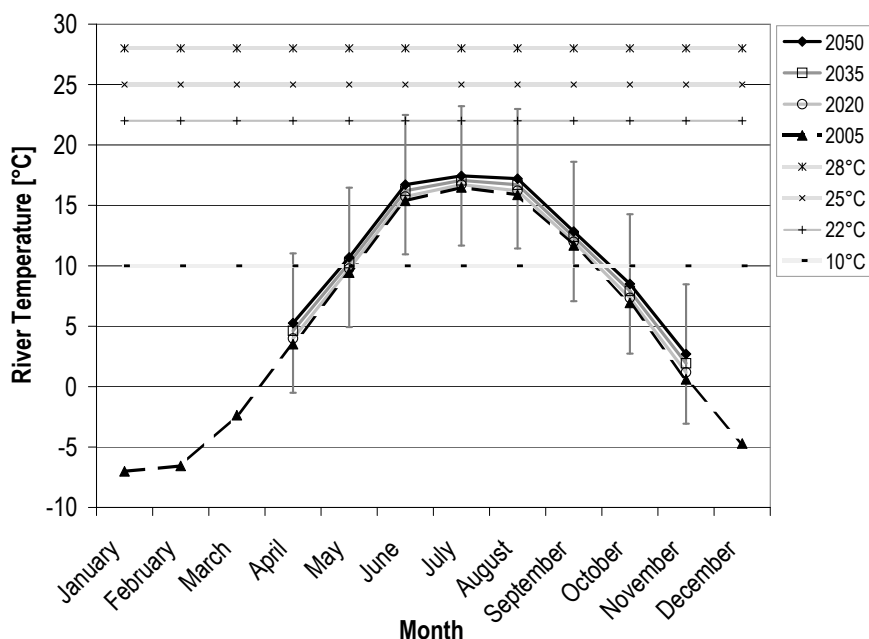
FIGURE 4.1.: *Monthly average river temperature estimates for the region SCA (including Sweden, Finland and Denmark) for selected years. Results based on (Erickson and Stefan, 2000; Ullmann, 2008). Regression estimates are only valuable for open waters (ice free), therefore no results are shown for the winter months from December to March.*

based on conventional cooling systems was reduced for the respective seasons by the factor of month, with temperatures above this threshold. The results of the water temperature analysis (Ullmann, 2008, Bachelor Thesis) indicate that from 2020 on, the monthly mean temperatures for rivers in the months July and August will reach values higher than 25 °C in southern European regions.

4.2.1. Available Cooling Technologies

To overcome possible shortages in power generation due to reduced water availability for cooling purposes, the model EuroMM includes different
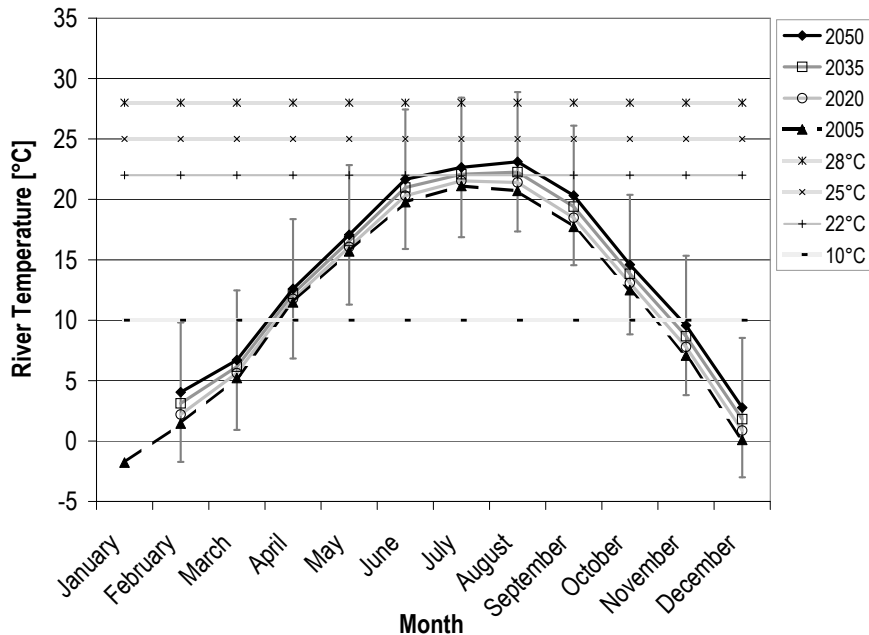
FIGURE 4.2.: *Monthly average river temperature estimates for the region HUSLE (Hungary and Slovenia) for selected years. Results based on (Erickson and Stefan, 2000; Ullmann, 2008). Regression estimates are only valuable for open waters, therefore no results are shown for the winter month January.*

technological alternatives. Besides the possibility of investing in more capacity using conventional cooling systems (e.g. once through cooling), the option of wet or dry cooling towers was available for all major electricity generation technologies. However, advanced cooling technologies are more expensive and usually consume more electricity or water then conventional cooling systems. Parameters, e.g. investment cost, variable operation and maintenance cost, electricity demand and water demand, were added to the electricity generation technologies, available in the baseline scenario. An overview of the parameters used, based on previous works (Birkinshaw, 2002; Zammit, 2004), is introduced in table 4.2. The variation in terms of investment cost, efficiency and costs for the water use are highly dependent on site specific conditions. For water costs,
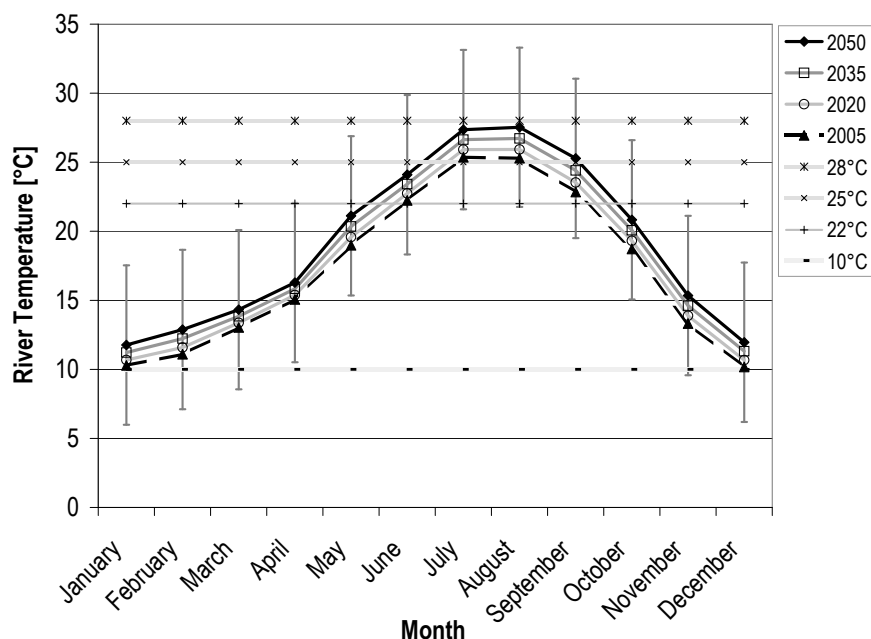
FIGURE 4.3.: *Monthly average river temperature estimates for the region IBE (Spain and Portugal) for selected years. Results based on (Erickson and Stefan, 2000; Ullmann, 2008).*

estimates range from 0.13 $/m^3 to 15 $/m^3, in very dry regions (Zammit, 2004). In this dissertation, an average cost of 0.23 $/m^3 was used, to reflect average costs. Efficiency losses due to higher electricity demand for the vans in dry cooling systems, range from 0.2% in coastal regions to 9.14% and higher under very hot conditions (Maulbetsch and DiFilippo, 2006). Average performance losses over the year were expected to be in the range of 2%, a value used to define dry cooling systems in EuroMM.

Hybrid cooling systems integrate wet cooling and dry cooling techniques in one. This system is giving utilities the option to trade off between reducing water demand (e.g. the cost for water) and the cost for electricity. However, the installation of such cooling system is even more depending on site specific parameters, as compared to wet cooling or dry cooling systems. This is due to the fact that two main operation modes

exist. Power plant operators would either run this system, to avoid va-
por plumes from wet cooling or to reduce water consumption. In case
of plume abatement, only minor advantages exist regarding water de-
mand reductions, compared to wet cooling tower. Additionally, this small
demand reduction is traded off for higher investment costs and reduced
electricity output. In the second operation mode, hybrid systems are used
for water conservation reasons which reduces evaporation in the range
of 30% to 80% compared to wet cooling tower systems. Due to the dif-
ficulty of implementing either of this possibilities in the cost optimization
model EuroMM, hybrid cooling systems are not considered in this study.
Additionally, it is expected that almost all new combined cycle plants will
be equipped with either wet or dry cooling towers exclusively (Birkinshaw,
2002).

4.3. Climate Change Impacts on River Runoff

As described previously, and in Reiter et al. (submitted), two hydrologi-
cal effects from climate change will influence river runoff, and therefore
possible power output of hydro power plants. Firstly, the annual water
balance is likely to change depending on the European region. The in-
fluence of climate change on the gross hydro power potential as well as
its impact on the already developed hydro power capacity, was studied
previously (Lehner et al., 2005). The changes in the annual hydro power
potential, based on assumptions derived from the PowerAce model as
described in Reiter et al. (submitted), were implemented in EuroMM. It is

TABLE 4.2.: *Assumptions on model input parameters used for the cooling in-
frastructure of power plants. The values are based on literature data
(Birkinshaw, 2002; Maulbetsch and DiFilippo, 2006; Zammit, 2004).*

Cooling system		Wet cooling	Dry cooling
Additional Inv. Cost	$[US\$/kW]$	6 - 8	40 - 100
Water Evaporated	Mm^3/PJ	100-760	-
VAROM	$[US\$/m^3]$	0.23	-
Losses	[%]	-	0.2%-9.1%

expected that average annual runoff is varying from approximately -50% in Bulgaria to +10% in countries such as Sweden or Norway (Reiter et al., submitted).

Secondly, a changing seasonal pattern of precipitation and snow/ice melting is likely to occur (Arnell, 1999). Mainly two precipitation patterns exist. One pattern is dominated by rainfall and evaporation, with a river runoff peaking in winter; the other pattern is dominated by snowfall and snowmelt, with a spring maximum (Arnell, 1999). The impact of climate change is expected to shift the pattern of snow-dominated regimes towards the rainfall-dominated regime, leading to earlier (winter) peak runoffs. In Nordic countries such as Norway or Sweden, the peaking runoff from snowmelt in spring will flatten out, whereas in southern countries, the runoff in summers is likely to decrease (Arnell, 1999). To translate the reduced runoff into EuroMM, the seasonal reservoir availability SRAF(Z) (where Z is the index for the respective season which in EuroMM is Winter, Summer or Intermediate), calculated for the calibration year is multiplied by the ratio of the runoff due to climate change and divided by the runoff in the baseline scenario. The SRAF(Z)-parameter is establishing the limit on total hydro power available, depending on the available capacity resulting in the seasonal utilization equation (see the simplified equation 4.1 based on Loulou et al. (2004)). In the equation 4.1, SRAF is the specified maximum reservoir availability for each given season and R_CAP is the installed hydro power capacity in the according region. These two parameters define together the maximum amount of the seasonal capacity available, which needs to be smaller or equal to the potential electricity generation from hydro power plants (R_TEZY).

$$SRAF * R\_CAP \leq R\_TEZY \tag{4.1}$$

Additionally, since the reduction of river runoff is also affecting the availability of water for cooling purposes in wet cooling towers, the availability factor for power plants using wet cooling towers was reduced accordingly. In some regions, this leads to a decrease of approximately 30% in summers for this type of plants.

4.4. Climate Change Impacts on Energy Demand

EuroMM used the fixed time slice set defined for MARKAL models. By implementing non-default fractions for seasonal demands of electricity and heat, the expected demand changes due to climate change were considered in this analysis. Based on demand estimates described previously (Jochem et al., 2008, chp. 6), the energy demands were expected to shift from winters to summers mainly in the residential and service sectors. A reduction in heating degree days of approximately 25-30% is observed in southern European regions, while in nothern Europe this reduction is likely to be 15-20% until 2050 (Jochem et al., 2008). In case of cooling degree days, Scandinavian countries may double the demand for additional space cooling, starting from relatively low levels. Countries such as Italy or Spain are likely to increase the space cooling demand by 30-40% (Jochem et al., 2008). The general trend in electricity demand for selected regions defined by its seasonal share is given in figure 4.4. This focus on seasonal shifts in electricity demand was important, since no storage capacities were available for period to period transfers of electricity, based on intermittend sources.

4.5. Other Impacts Included in EuroMM

4.5.1. Electric Resistance

Due to the average temperature rise, the electric resistance of transmission lines is likely to increase and therefore directly impact losses in the electricity network. The equation 4.2 defines the relationship between electric resistance and ambient temperature, where ρ is the electric resistance of a given material, with the temperature coefficient α of the specific conductor. $\rho(T_0)$ is the specific resistance for a given reference temperature.

$$\rho(T) = \rho(T_0) * (1 + \alpha * (T - T_0)) \qquad (4.2)$$

Based on estimates for average air temperatures in Europe in 2005, the resistance change for electric conductors was calculated for the coming
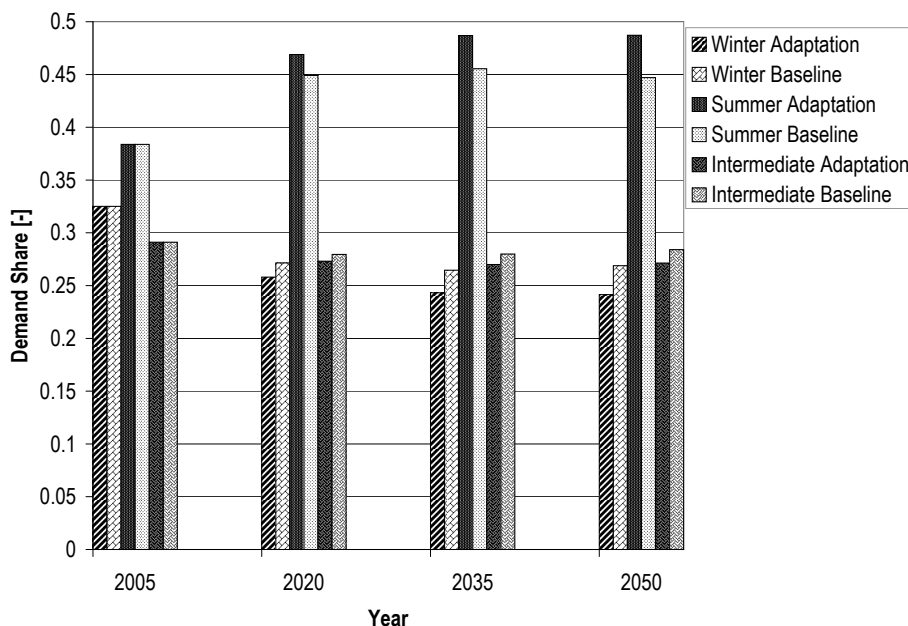
FIGURE 4.4.: *Shift in electricity demand from winters to summers for the region IBE (Spain and Portugal), derived from Jochem et al. (2008, chap. 6). The demand share defines the electricity demand in each season divided by the annual electricity demand in the according year. Data is given for the baseline and the adaptation scenario. Compared to the baseline assumptions, the demand for electricity in summers increased further under climate change conditions (adaptation scenario) due to higher demand for space cooling.*

decades and applied as relative change on the given transmission losses derived from Eurostat (2005).

4.5.2. Water Demand for Cooling Purposes

In EuroMM, the water demand and consumption of power plants is modeled as a material flow for each type of power plant which is depending on cooling water. As a first estimate and due to a lack of consistent data, all existing power plants are modeled for using once through cooling systems (OTC). The information on cooling systems in Europe is scarce and

it is assumed that the general estimates were close enough for comparison reasons (Vassolo and Döll, 2005). The water demand for different power plant types using either wet cooling towers (WTC) or once through cooling systems was also implemented (see table 4.3), based on data obtained (Goldstein et al., 2002).

4.6. Review of Scenario Drivers

As described in section 4.1, EuroMM was used to analyze the potential impact of climate change on the European energy conversion sector. The scenario analysis relies on the input assumptions on renewable potentials, nuclear energy deployment, emission taxes and energy prices, among others (see table 4.4 for an overview of the exogenous driving parameters). Additionally, the impacts of climate change, as described in this chapter, were considered for the development of the adaptation scenario. Specifically, an average river temperature regulation threshold of 25 °C was used to estimate needs for investments in advance cooling technologies. Changes in final energy demand were also considered, and the impacts on hydro power potentials were included.

4.7. Results for the Adaptation Scenario

4.7.1. Electricity Generation

The analysis of the future development of the European electricity system under the influence of climate change indicated that total electricity demand by 2050 will be around 2% higher, as compared to the baseline. A significant share of the growing electricity demand is covered predominantly by coal based power generation (see figure 4.5). In the absence of CO_2 emission reduction targets, electricity generation using coal is highly competitive due to the comparatively stable and low international coal prices (see figure 3.2), abundant coal reserves in some EU-member countries (e.g. Poland, Germany, Czech- and Slovak Republic) and the availability of advanced coal-fired power generation technologies. In absolute terms, coal based electricity generation is likely to increase from

TABLE 4.3.: *Water demand and consumption for different power plant types and different geographical regions based on Goldstein et al. (2002). In this analysis only values for northern and intermediate regions were applied on the available regions and technologies. OTC indicates once through cooling systems and WCT stands for wet cooling tower. Evap. stands for evaporated water, lost for the river system.*

Type of plant	Water withdrawal			Water evap.	Water returned			Cost
	north Mm^3/PJ	intermediate Mm^3/PJ	south Mm^3/PJ	average Mm^3/PJ	north Mm^3/PJ	intermediate Mm^3/PJ	south Mm^3/PJ	average $M\$/PJ$
Steam plant (OTC)								
fossil	21030	36802	52575	315	20715	36487	52260	0.07
nuclear	26288	44689	63090	421	25867	44268	62670	0.10
Combined Cycle plant (OTC)								
fossil	7886	14327	21030	105	7781	14222	20925	0.02
Steam plant (WCT)								
fossil	526	578	631	505	21	74	126	0.12
nuclear	841	999	1157	757	84	242	400	0.18
Combined Cycle plant (WCT)								
fossil	242	242	242	189	53	53	53	0.04
Gasification Combined Cycle plant (WCT)								
fossil	263	263	263	189	74	74	74	0.04
water for gasification				137				
total				326				

69

TABLE 4.4.: *Overview of the main input assumptions to the model EuroMM for the adaptation scenario. The exogenous input parameters (marked with *) were derived from partners of the European ADAM project (Jochem et al., 2008).*

Scenario drivers adaptation	Additional information
Energy demand*	Relatively stable demand for all final energy carriers until 2050. Demand shift from winters to summers
Fuel prices*	Oil price in 2050 at 180% of 2005-values, other fuels between 125% (biomass) up to 270% (lignite) of 2005 prices in 2050
Technology assumptions*	Cost, reduced efficiencies for thermal electricity generation, changes in power plant availability (based on own estimates)
CO_2-tax	$10 per ton of CO_2
Nuclear policies	Country specific (e.g. nuclear phase-out in Germany and Sweden)
Population growth*	Decline of -0.1% per year until 2050. Indirectly applied in EuroMM via final energy demand assumptions
GDP-growth*	Average increase by 1.5% per year until 2050. Indirectly applied in EuroMM via final energy demand assumptions

1000 TWh in 2005 to 1500 TWh in 2050 covering 34% of total electricity generation in 2050.

In comparison, the share of nuclear power in total electricity production remains roughly constant. After a period of decline until 2020, due mainly to the impact of nuclear phase-out policies of some EU-member countries (e.g. Lithuania, Germany), total investment will begin to increase again, as countries with higher social acceptance of nuclear power replace existing capacity and install additional power plants. In this scenario, nuclear
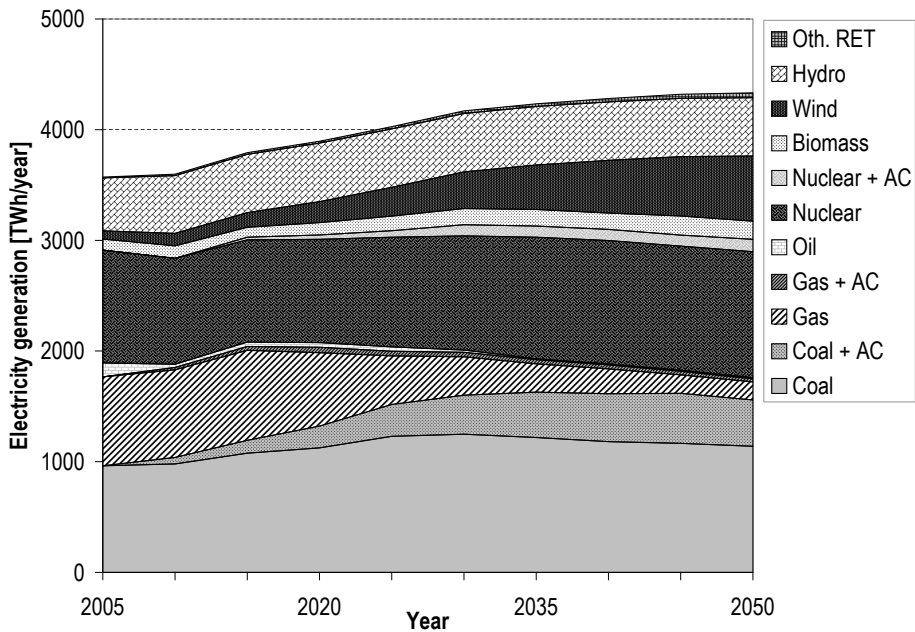
FIGURE 4.5.: *Electricity generation under the consideration of climate change in EU27+2. Data is given for major energy carriers such as Coal (including hard coal and lignite), Gas (natural gas and derived gas), nuclear, and renewable sources. Oth. RET stands for other renewable technologies including solar technologies, geothermal and ocean based electricity generation. AC stands for technologies equipped with advanced cooling facilities such as dry and wet cooling towers.*

based electricity generation is contributing with approximately 28% to total generation in 2005 as well as in 2050.

Unlike coal and nuclear power, natural gas plays only a minor role in electricity generation in Europe in this adaptation scenario. The depletion of natural gas reserves in Europe together with a high international gas price (compared to coal market prices) represent unfavorable framework conditions for new investments in electricity generation based on natural gas (assuming the absence of significant climate change mitigation policy). Gas based electricity generation is likely to decrease from 800 TWh in 2005 to 200 TWh in 2050.

As indicated previously, future river temperatures may reach values higher than 25 °C in southern European regions in 2020 (e.g. Spain, Portugal, Italy, Greece, Romania and Bulgaria). To avoid reduced electricity output from thermal power plants and to cover increased electricity demands in summer, a need for increased deployment of electricity generation technologies (in aggregate), together with installation of advanced cooling systems for new thermal power plants, could be identified for the near future. Increased river temperatures in southern Europe means that by 2050 almost all thermal power plants (Rankine cycle) need advanced cooling systems to avoid decreased output (including shut-downs) during summer months (see figure 4.6). Only the electricity generation based on natural gas driven gas turbines and renewable electricity generation was unaffected by reductions in cooling water availability in southern Europe. Thus, electricity imports from regions without limitations in power production due to climate change are becoming more important for southern Europe. As a result, the electricity demand in southern Europe is likely to be 7% higher as compared to the baseline in 2050 whereas electricity imports will be almost 18% higher in the adaptation scenario in 2050.

Also in the future, renewable energy technologies (RET) continue to play an important role in the European energy system, even in the absence of distinct mitigation efforts. Compared to the development of RET in the baseline, the total electricity generation under conditions of climatic change remains similar. Only the contribution of the different technologies changes slightly. The share of renewables in electricity generation increases to 33% in Europe, including hydro power (see figure 4.5). Regarding the use of RET, wind onshore and offshore energy contributes with a share of 16% towards the end of the time horizon considered. The use of solid biomass for electricity and combined heat and power generation remained almost constant and amounts to approximately 180 TWh or 4% of total generation by 2050.

The hydrological impacts of climate change will affect not only the availability of water for cooling purposes, but also the availability of water for hydro power production. Looking at the hydro power production in Eu-
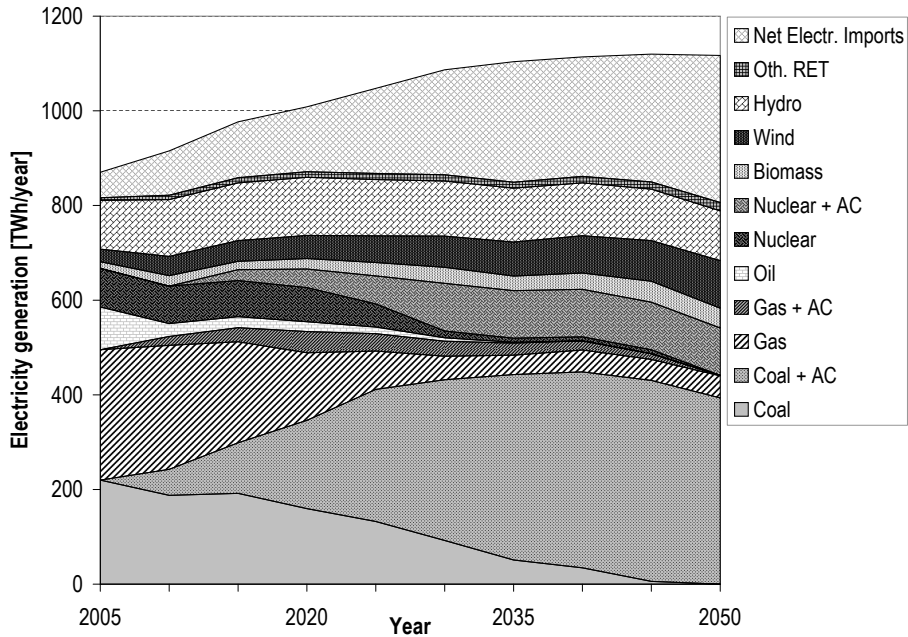
FIGURE 4.6.: *Electricity generation based on various primary energy carriers in the adaptation scenario for southern Europe (including Portugal, Spain, Italy, Greece, Bulgaria and Romania). AC stands for technologies equipped with advanced cooling facilities such as dry and wet cooling towers.*

rope, it decreased by about 6% in 2050, as compared to the baseline scenario. However, observing developments at the regional level, one can see that some regions experience considerable changes in hydro power production. In southern European countries, the hydro power production will decrease by approximately 22% to 2050, in the adaptation scenario compared to the baseline, whereas Nordic countries profit of increased potentials of around 4% in electricity output generated by hydro power plants. For Switzerland, Austria and France, three of the five countries with the highest contribution to total hydro power generation in Europe, it is expected that the total output will decrease by approximately 7% in 2050 compared to the baseline. In Eastern Europe hydro power generation is expected to decrease by approximately 8% in 2050.

However, individual countries such as Bulgaria expect an even stronger decrease by up to 50% (see also Reiter et al. (submitted) for additional information).

In addition to the higher demand for electricity in the adaptation scenario, it is estimated that the transmission losses due to higher electric resistance in overhead lines add up to 1% of total electricity demand in 2050 across Europe.

4.7.2. Electricity Trade

As indicated above, electricity trade is becoming more relevant for some regions in this adaptation scenario. Due to the reduction of generation efficiency and availability in southern Europe, electricity imports to southern Europe increase by 18% until 2050. Depending on the electricity trade connection, trade flows may increase by up to 80%. While Italy is the region with highest growth in imports from regions outside southern Europe, the trade within southern Europe is reduced. Greece and Bulgaria decrease their export volumes by up to 45% until 2050 compared to the baseline.

4.7.3. General Energy

Primary Energy

The total primary energy supply (TPES) in the adaptation scenario does not change considerably, compared to the baseline scenario in aggregated terms (see figure 4.7), varying between 80 EJ and 82 EJ until 2050. The main resource of energy is oil together with oil products, with a share of 33% in 2050 which is equivalent with a reduction of 5% compared to the year 2005. Increasing shares of TPES were obtained from coal, nuclear and renewable fuels, growing $\approx$ 1.5% and 7.5% for coal and renewables, respectively. Natural gas, with the second largest share in 2005 becomes less important, and only contributes with 17% to the total primary energy supply. Compared to the baseline, no relevant changes in fuel shares of the TPES was found since no relevant incentives for fuel switches (e.g. CO_2-taxes) were introduced in this scenario. The reduction

of fuel demand for heating purposes is widely compensated by increased demands for cooling energy.

Low Temperature Heat

As mentioned previously, the demand for low temperature heat (district heat) is likely to be changed under climate change. The low temperature heat (LTH) demand will mainly be supplied by inexpensive coal, and biomass, particularly municipal wastes and increasing shares of wood fuel, for combined heat and power plants. By 2050, gas-based district heat production will be replaced and heating-oil based plants are phased out earlier, between 2020 and 2030, (see figure 4.8) due to high fuel prices. The production of low temperature heat only represents a minor market activity below 2.3 EJ per year with declining trend down to 1.8 EJ in 2050, due to decreasing demand for district heat in buildings in the coming decades. The reduction in district heat demand amounts to 7% in 2050 in the adaptation scenario.

Fuel Production

In this adaptation scenario, the demand for alternative fuels is comparable to the results in the baseline scenario. Due to environmental regulations in place in 2005, the demand for biofuels increases from 200 PJ in 2005 to approximately 1000 PJ in 2020. Only slightly increases are observed thereafter (up to 1100 PJ in 2050). In the 2020s, the main fuel is biodiesel based on oil crops, with a share of 69% in total production. The remaining share of 31% is biodiesel based on wood residues, and ethanol from cellulosic biomass (see figure B.2 in the appendix). These two technologies become available from 2020 in EuroMM and the total output of the respective fuels highly depends on the initial capacity. However, in the long run, these two technologies reduce the share of biofuels from oil crops to 21% and therefore prove more competitive.
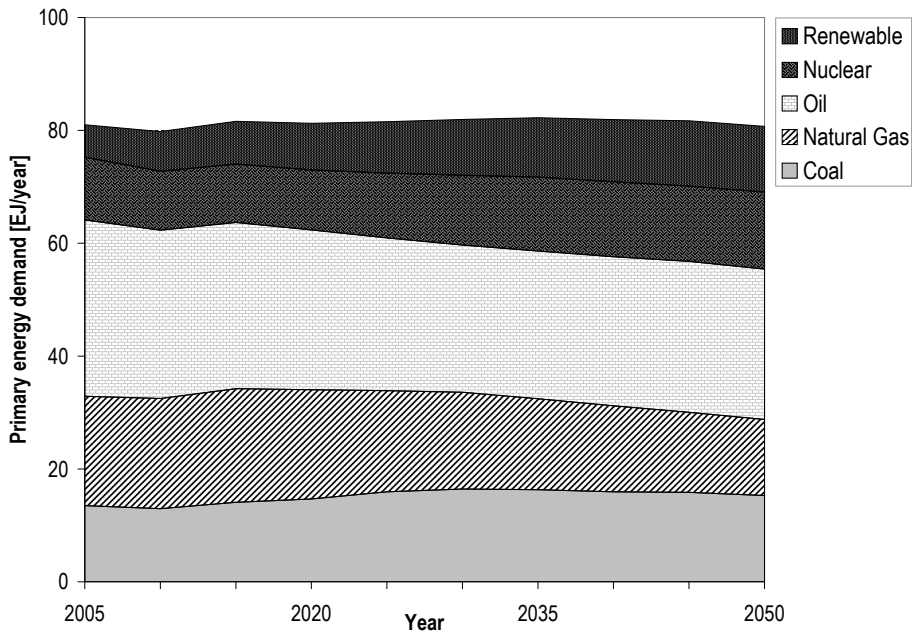
FIGURE 4.7.: *Primary Energy demand shown for various energy carriers under climate change assumptions (adaptation scenario). Coal includes demand for hard coal and lignite, renewable sources include biomass, hydro, solar, geothermal, ocean and wind energy.*

4.7.4. Economic Implications of Adapting the Energy Conversion Sector to Climate Change

As mentioned earlier, European regions are affected differently by climate change. In this analysis, the main burden of adapting the energy conversion sector to climate change will be carried by southern Europe. Increasing energy demands for space cooling and decreasing efficiency in power generation were both drivers for additional investment needs, including investments in advanced cooling technologies. Compared to the baseline scenario, the investment in southern Europe are expected to be 13%-14% higher in 2050 in the adaptation scenario (see figure 4.9) amounting to approximately $50 billion by 2050. However, to overcome reduced power generation efficiency and increased electricity demands,
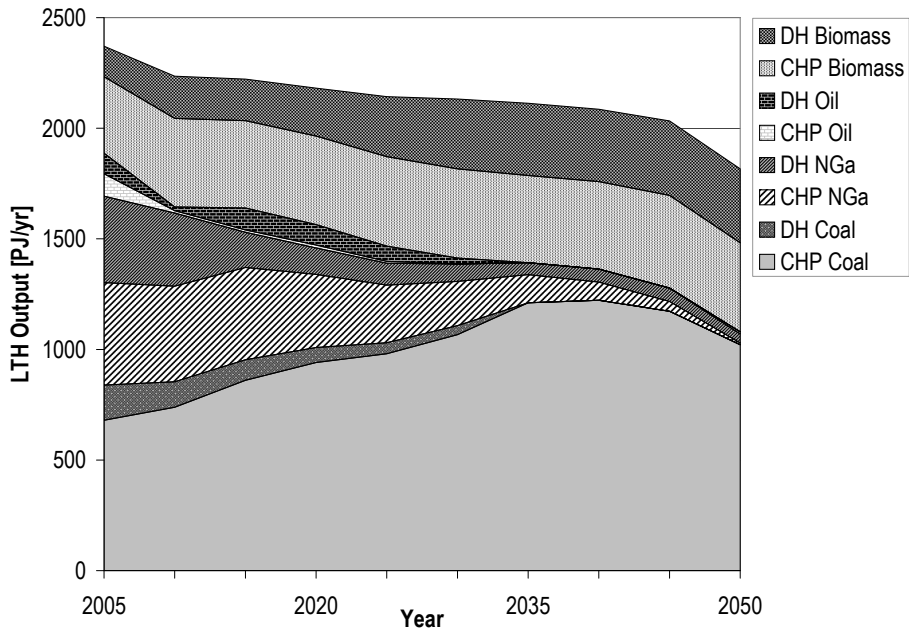
FIGURE 4.8.: *District heat generation by fuel type in EU27+2 until 2050, adaptation scenario. Heat generation is based on CHP technologies as well as district heat plants (DH) for various energy sources such as coal (including hard coal and lignite), natural gas and biomass (including waste products).*

southern Europe also relys on electricity imports from neighboring countries (e.g. France), less affected by climate change.

For all of Europe, the cumulative undiscounted investment in the adaptation scenario is approximately $1.7 trillion until 2050. Since the output of renewable electricity generation hardly changes, compared to the baseline scenario, the total investment in the adaptation scenario exceeds the one in the baseline by 5-6% in 2050. The cumulative discounted total system cost, including investments, operation and maintenance cost, production cost of domestic fuels and transaction costs of fuel imports, are in the range of $4.2 trillion until the end of the modeled time horizon and therefore less than 1% higher, as compared to the baseline. Addi-

tionally, the expenditures on fuels from sources outside EU27+2 needs to be considered. The cumulative discounted cost for fuel imports to Europe were in the range of $6.5 trillion, equal to the findings of the baseline scenario.

4.7.5. Water Demand

Given the fact that water resources are recognized as highly vulnerable to climate change in the future (Parry et al., 2007), the water demand for cooling purposes in power plants is of high interest. However, exact numbers on total water withdrawal and consumption are difficult to obtain. According to Eurostat (Eurostat, 2008), the total water withdrawn in Europe is in the range of 140 billion m^3 in 2005 for countries, where data is available. In this list of public available data, large countries such as Germany, Italy or the United Kingdom were not providing any information, and a high water withdrawal is expected. A similar situation was found for the data about water withdrawal in the electricity generation sector, in the range of 70 billion m^3, for the same number of countries according to Eurostat (Eurostat, 2008). In comparison, Vassolo and Döll (2005) estimate the amount of water withdrawn in 1995 to 122 billion m^3 for cooling purposes of power plants in Europe, whereas the Eurostat database (Eurostat, 2008) records 57 billion m^3 (limited number of countries where data is available) for the same year and purpose.

Given the uncertainty of the number of power plants with wet cooling or once-through cooling systems in Europe (Vassolo and Döll, 2005), in EuroMM it was assumed that only once-through systems were in place in 2005. Together with the different cooling technologies implemented in EuroMM, it was found that the water withdrawal for the calibration year is in the range of 214-220 billion m^3. Compared to findings in literature, the total amount of water withdrawn in this analysis is overestimated by approximately 40% (including the higher electricity generation in Europe in 2005, compared to 1995), whereas the total water consumption is underestimated by 40%. In previously findings (Vassolo and Döll, 2005), the deviation between estimates and public available data for water withdrawal was in the range of more than 30% for some countries, and it
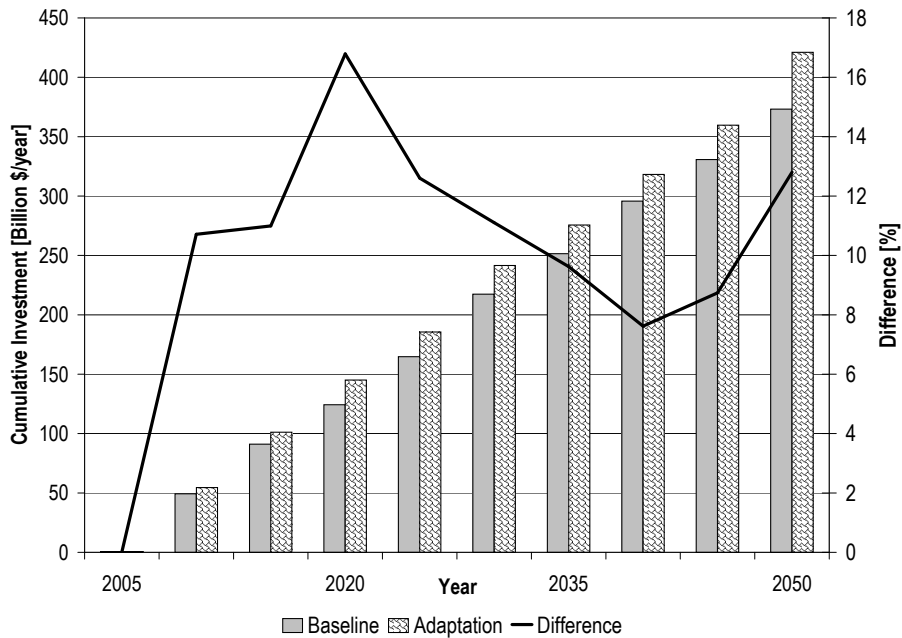
FIGURE 4.9.: *Cumulative investments (left axis) for various electricity genera-*
tion technologies as well as other energy conversion in southern Eu-
rope (comprising Bulgaria, Romania, Greece, Italy, Spain and Portu-
gal). Right axis: difference of cumulative investments between adapta-
tion scenario and baseline scenario for southern Europe.

was not clear, which European countries were considered to obtain water withdrawal rates. By increasing the use of power generation systems using wet cooling for the calibration year in EuroMM, the results of EuroMM could be improved, but due to the uncertainty about the actual number of installed cooling systems, it was decided otherwise.

Further results of EuroMM indicate, that in this adaptation scenario, the water withdrawn in the future is likely to decrease by approximately 9-10% until 2050 (see figure 4.10). This is in contrast to the baseline scenario where the water whithdrawal increased by 16-17% until 2050. In line with the switch to dry-cooling systems for power generation in southern Europe, the water savings are realizable in southern Europe. Thus, it is

estimated that approximately 500 million m^3 of freshwater could be saved per year in the future, due to reduced evaporation rates.

4.8. Summary of Results

As can be seen from the analysis presented here, even in the absence of efforts to reduce greenhouse gas emissions, significant technical change will be needed in the European electricity sector, to adapt to the impacts of climate change. In particular, climate change will pose major adaptation challenges for southern Europe. To avoid reduced electricity output from thermal power plants, and to cover increased electricity demand in summer, this analysis indicates the need for increased deployment of electricity generation technologies (in aggregate), together with installation of advanced cooling systems for new thermal power plants, already in the near future. The increased average river temperatures in southern Europe mean that by 2050, all thermal power plants will need advanced cooling systems in this region. As a result, a significant share of all thermal electricity generation in Europe will be from power plants with advanced cooling systems. Additionally, electricity trade becomes more important, since the electricity generation in central Europe is less affected by climate change. Southern European countries could profit from this, by increasing its imports from central Europe, which relies on abundant coal reserves and nuclear capacity, and the potential for growth in electricity generation and trade.

4.9. Discussion and Conclusion

The impacts of climate change on the energy conversion sector in Europe have been examined in this study. The main difficulty in obtaining reasonable estimates on infrastructure changes, and associated costs was translating site-specific information about environmental parameters (e.g. river runoff and temperature) into aggregate model assumptions, describing future developments of countries and groups of countries. In the literature, there is data available on local impacts of climate change on
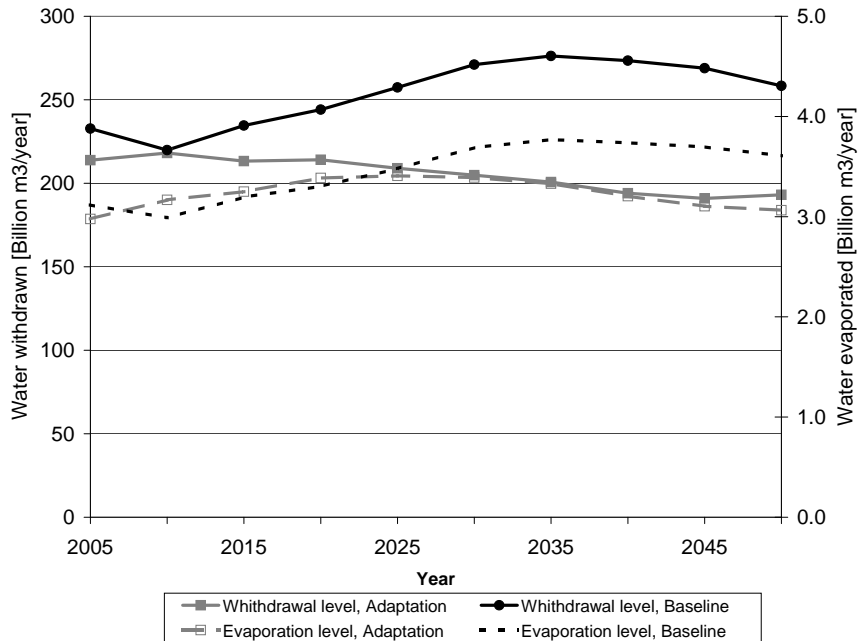
FIGURE 4.10.: *Water demand (withdrawal level, left axis) in Europe for cooling of thermal power plants in the adaptation scenario compared to the baseline. The right axis is showing the amount of water which is evaporating after waters have been used for cooling purposes.*

different sectors, regions and even communities, including factors such as energy demand changes, due to higher temperatures (Isaac and van Vuuren, 2009). However, on the large scale of countries and country associations, such as the European Union, the impacts on the energy conversion sector, especially electricity generation have hardly been investigated. These challenges were addressed by extrapolating local impacts to large scales, and by including available data on country level in the European MARKAL model (e.g. changes in precipitation). It is expected that by using additional information from other sources (e.g. additional GIS-based data), the robustness of the analysis could be improved.

In this analysis, a potential future conflict between environmental regulations and the security of the electricity supply has been identified.

Specifically, climate change is likely to increase river temperatures in many parts of Europe (particularly southern Europe) above regulatory thresholds governing whether the water can be used for cooling thermal power plants. A strict application of these thresholds may force the partial or complete shutdown of some thermal power plants during summer months, which may threaten the electricity supply. Thus, authorities may be tempted to temporarily suspend these environmental regulations. This situation already occurred in the hot summer of 2003, where French and German authorities allowed the utilities to temporarily ignore the European fresh water directive (de Bono et al., 2004; Homobono, 2008; IKSR, 2006; Lacoste and Trouvé, 2004). However, this allowance comes with the cost of damages to the ecological system. By analyzing future conditions of water runoff and temperature, utilities will be able to satisfy the environmental regulations by investing in advanced cooling technologies.

It should be mentioned that one adaptation measure which has not explicitly been analyzed, is the possibility to use seawater for cooling thermal power plants, thereby avoiding the problem of reduced cooling water availability, and hence decreased power output or complete shutdowns, due to high water temperatures. However, other factors such as salt water corrosion, and additional flood and storm surge protection measures, in response to rising sea levels, would be needed. Moreover, fuel transportation and transmission costs are likely to be higher, given that this option is currently only attractive for a small number of power plants in Europe.

Under the assumption that hot weather extremes will occur more frequently due to climate change (see Easterling et al. (2000) and Heino et al. (1999)), central European countries are expected to face shortages of their electricity production in summer, similar to the impacts observed in 2003. Accordingly, additional investments will be necessary in those regions, to ensure sufficient reserve capacity is available, to guarantee stable grid operation. These extreme events however, were not considered in this scenario analysis. Additionally, it is noted that today, nuclear power plants generally undergo refueling and maintenance during summer months, and are not available for power production. With grow-

ing electricity demand, combined with reduced generation efficiency and availability, it is likely that more of these plants will need to remain online during summer, to prevent from possible shortages. This will require changes to the planning of scheduled downtime well in advance, and additional reserve capacity. This represents an area for further investigation.

Importantly, not all countries within Europe are equally affected by climate change, and some countries may even profit. Northern European regions are likely to realize fuel savings, due to reduced space heating demands, together with increasing potentials for hydro power generation. Additional investments in new dams and changed reservoir management will offer Nordic countries the chance to increase their output of renewable electricity.
Looking at Southern regions, it should also be mentioned that some of the potential impacts not considered here, such as the higher incidence of extreme events (e.g. heat waves or storms), and additional electricity needs for irrigation and desalination, could pose further adaptation challenges to the electricity sector. Furthermore, it may be necessary to increase reservoir volume in southern European countries, to overcome the losses from reduced river run-off. However, this may be only partially effective if it leads to larger reservoir surface areas, and hence greater evaporation. To overcome the reduction of hydro power generation, southern European regions have to invest in additional thermal and other renewable power generation, and import additional electricity.

In general, one should take into account that there are a number of uncertainties and limitations to the analysis presented here. Firstly, there is limited knowledge on likely changes to river flow patterns with climate change, important for estimating cooling water availability for thermal power plants. In addition, there is a high level of uncertainty associated with the hydro power potential data, derived from climate models, thus, the estimates of hydroelectric generation under climate change are also uncertain. Moreover, extreme events are excluded entirely from this analysis, given the limited understanding of how these will vary in the future, although they have the potential to affect almost every aspect of energy supply and demand. To analyze the impacts on the energy con-

version sector in more depth, some further research would be needed to improve the quality and quantity of data concerning the impacts of climate change on large scale. This includes reliable data about the change in weather conditions, especially extreme events, and their return periods since these extreme events are likely to be the driving cost factors for reinforcement and uprooting of infrastructure. In case of extreme floods, the change of return periods of a nowadays event with a 100 year return period is estimated to occur every 20 to 50 years in case of climate change (Dankers and Feyen, 2008) until the end of the century, but a high uncertainty is given for these results. The reduced return period is in the range of the lifetime of many technologies, implying more costly flood protection measures and investments.

4.9.1. Policy Implications

In absence of mitigation efforts, utilities and regulatory authorities should consider the planning of appropriate investments and policy measures to guarantee secure power generation under climate change. To avoid conflicts with environmental regulations, an integrated water management is needed, to ensure the best possible use of resources. An additional incentive for switching from wet to dry cooling in regions where water resources are scarce, is the water savings which could be achieved and redirected into other sectors, to fulfill increasing demands (e.g. more irrigation in agricultural sector).

On European level, it might be necessary to establish compensatory measures between northern and southern regions, to ensure an equitable sharing of the burden of adaptation in Europe. However, an integrated approach will be needed, to achieve this goal within the EU. It might be noteworthy that these compensatory measures are likely to be needed between regions which profit from climate change, and others which don't.

5. Climate Change Mitigation

5.1. Introduction

To avoid serious damages from climate change, large efforts are needed in Europe and the rest of the world, to reduce the emissions of greenhouse gases. In this chapter two different climate change mitigation targets are analyzed, regarding their implications on the European energy conversion sector. Using the cost-optimization model EuroMM, specific questions about possible technology pathways to achieve such targets were analyzed. In focus were different emission targets and their associated costs, the deployment of different CO_2-free technologies such as nuclear, fossil generation with CCS and renewable technologies.

Depending on the underlying probability to limit climate change to below 2 °C increase in 2100 (see section 2.3.5 for further details about different climate targets), different GHG concentrations need to be achieved. In this specific analysis, emission pathways were set to limit GHG concentrations to 450 ppm CO_2-eq and 400 ppm CO_2-eq, corresponding to probabilities of 50% and 80%, respectively, to stay below a temperature increase of 2 °C until 2100, compared to pre-industrial levels. Both scenarios are further described in this chapter. In section 5.2, the emission reduction scenarios are further introduced, followed by the sections 5.3 and 5.5 describing the results for the 450 ppm CO_2-eq and 400 ppm CO_2-eq scenario, respectively. The results are further discussed and compared in section 5.7.

5.2. Scenario Assumptions and Inputs

As described in section 3.2.2 some changes regarding energy demand and fuel prices, among others, needed to be implemented in EuroMM to

describe possible mitigation scenarios for the European energy conversion sector. Accordingly, the 450 ppm CO_2-eq mitigation scenario in this study defined a greenhouse gas concentration target, translating into an emission reduction of -65% for CO_2-only until 2050, compared to 2005. An emission pathway consistent with this target has been developed for the period 2005-2050, derived from an analysis with the energy sector model POLES (Schade et al., 2009, chap. 4). This pathway was used to specify annual emission caps for Europe whereas no country specific emission caps were defined. In addition, a demand scenario for the mitigation case that included end-use efficiency measures and behavioural changes was applied (see figure 3.5 and section 3.2.3 as well as table 5.1 for further details on scenario drivers). The emission cap together with the demand scenario were key inputs for the EuroMM model, used to analyze the full energy system.

Additionally, the potentials for renewable energies were used, as described in section 3.3.3. However, for this analysis the contribution of wind power was limited to 30% of total generation in each region since it remains unclear if higher shares of intermittent sources can be integrated in the electricity grid. In some of the regions described in EuroMM (e.g. Great Britain (GBI) or Spain and Portugal (IBE)), the potential for wind power generation is above this threshold. To further analyze this issue, implications of the 30% limitation of wind power penetration into the market were investigated. These resutls are presented in chapter 6.

It is noteworthy that in the mitigation scenarios described here, no potential impacts on the energy system due to rising temperatures were considered. Although average air temperature is expected to increase given the current greenhouse gas concentrations, the potential impacts of higher temperatures stay below certain thresholds (e.g. river temperature regulations as described in section 4.2) in the considered time horizon up to 2050. However, for an analysis of mitigation scenarios until 2100 it is recommended to include these changes.

In a comparable way to the 450 ppm CO_2-eq scenario, a 400 ppm CO_2-eq scenario was set up in this analysis. However, additional final energy

TABLE 5.1.: *Summary of the main input assumptions for the mitigation scenarios. The input exogenous parameters (marked with* *) *were derived from partners of the European ADAM project (Schade et al., 2009).*

Scenario-drivers mitigation	Additional information
Energy demand*	Declining demand for all final energy carriers until 2050 due to assumptions on efficiency improvements
Fuel prices*	Oil price 80% of 2005 in 2050, other fuels between 125% (natural gas) up to 270% (lignite) of 2005 prices in 2050
Technology assumptions*	Cost, availability, efficiency
CO_2 emission cap*	Targets for achieving 450 ppm CO_2-eq and 400 ppm CO_2-eq
Nuclear policies	Country specific (e.g. nuclear phase-out in Germany and Sweden)
Population growth*	Decline of -0.1% per year until 2050. Indirectly applied in EuroMM via final energy demand assumptions
GDP-growth*	Indirectly applied in EuroMM via final energy demand assumptions

demand technologies were included for transportation in EuroMM in this scenario based on data previously generated at PSI (Gül, 2008). These technologies describe various car-types for passenger transport, which were used to cover the final energy demand, expressed in passenger-kilometers per year. The demand technologies which were described by different drive trains are defined for various fuel types (e.g. biofuels, hydrogen, and advanced combustion technologies). Therefore, some modifications to the original demand scenario based on Schade et al. (2009, chp. 9) were introduced. In a first approach to fully model the transportation sector in EuroMM, the demand for fuels in EuroMM was transformed into a demand for passenger-kilometers using the efficiencies of specific drive trains (Gül, 2008). Depending on the fuel used for transportation

(gasoline is exclusively used for passenger transport, whereas diesel is also used for freight transportation), the direct fuel demand was reduced in EuroMM between 12% for diesel and up to 60% for gasoline, and replaced with the according demand for passenger-kilometers. In this way, the model gaines partly freedom to fulfill specific demands by demand technologies specified in EuroMM and is therefore able to further reduce greenhouse gas emissions outside the electricity sector.

These modifications to the model were necessary to reproduce the given demand results (Schade et al., 2009, chp. 9), and to analyze further scenarios of the energy conversion sector, which are described in the following chapter. Additionally, in a later stage, the model can be further extended to fully depict the European transport sector analyzing different scenarios for transport demand.

The 400 ppm CO_2-eq constraint forces the model to reduce emissions until 2050 by 80% compared to 2005, allowing for less than 920 Mt of CO_2 released to the atmosphere per year (more about this reduction target can be found in chapter 2).

5.3. Results for the 450 ppm CO_2-eq Scenario

5.3.1. Electricity Generation

The modeling results show that the achievement of ambitious climate targets requires a complete transformation of the energy system. This transformation includes a substantial increase in the use of renewable energy technologies in Europe. Together with the assumed demand reductions, a considerable shift away from fossil fuels in the electricity sector is achieved. In the 450 ppm CO_2-eq scenario, the share of electricity from renewable sources increases from 19% in 2005 to 57% in 2050. Major sources of renewable electricity are wind- and hydro power (25% and 20%, respectively), whereas other renewables only contribute by 11% to total electricity production. Nuclear power keeps its share of 28% over the modeled time horizon, whereas the contribution of fossil generation decreases from 53%, to less than 15% in 2050 (see figure 5.1). It is noteworthy that in this mitigation scenario, the contribution of wind power to

total generation was limited to 30% in each region. In section 5.4 and
chapter 6, this issue is further described.

Looking at different regions in more detail, it is found that the develop-
ment of the electricity sector varies across Europe (see table 5.2). Based
on the historically grown infrastructure, including different policies on the
use of nuclear technologies, major regions developed their technolog-
ical portfolio in different directions. For instance, Nordic countries (in
this dissertation also referred to as "North" includes the countries Nor-
way, Sweden, Finland and Denmark) increasingly use their renewable
potentials based on hydro power, wind power and biomass for electricity
generation. In 2050, these countries rely by more than 90% on electricity
from renewable sources. The remaining share (6%) is covered by nuclear
power, and natural gas based electricity generation. Other regions, such
as eastern Europe, rely more on fossil generation until late in the mod-
eled time horizon. This is due to the existing fossil fuel based infrastruc-
ture and the availability of large domestic coal reserves, which are used
for electricity generation. However, specially in this region, a large share
of electricity is exported to neighboring countries. In eastern Europe (in
this dissertation also referred to as "East" includes the countries Latvia,
Lithuania, Estonia, Poland, Hungary, Slovenia, Czech Republic and Slo-
vak Republic), less than 30% of electricity generation is CO$_2$-free in 2050,
with wind power as the largest renewable source, contributing by 16% to
total generation. Western Europe (in this dissertation also referred to as
"West" includes the countries Germany, France, Belgium, Luxembourg,
The Netherlands, Austria, Switzerland, United Kingdom and Ireland) con-
tinues to use nuclear power with a similar output as 2005 (approximately
730 TWh in 2050), and an increasing output of wind power (380 TWh in
2050). Less than 7% of total generation is based on fossil fuels in 2050
(105 TWh in 2050) in this region. Southern Europe (in this dissertation
also referred to as "South" includes the countries Portugal, Spain, Italy,
Greece, Bulgaria, Romania, Malta, Cyprus) relies on a mix from various
sources, including biomass, wind power, hydro power and nuclear elec-
tricity, as well as fossil generation and additionally, covers approximately
30% of its electricity demand by electricity imports in 2050.
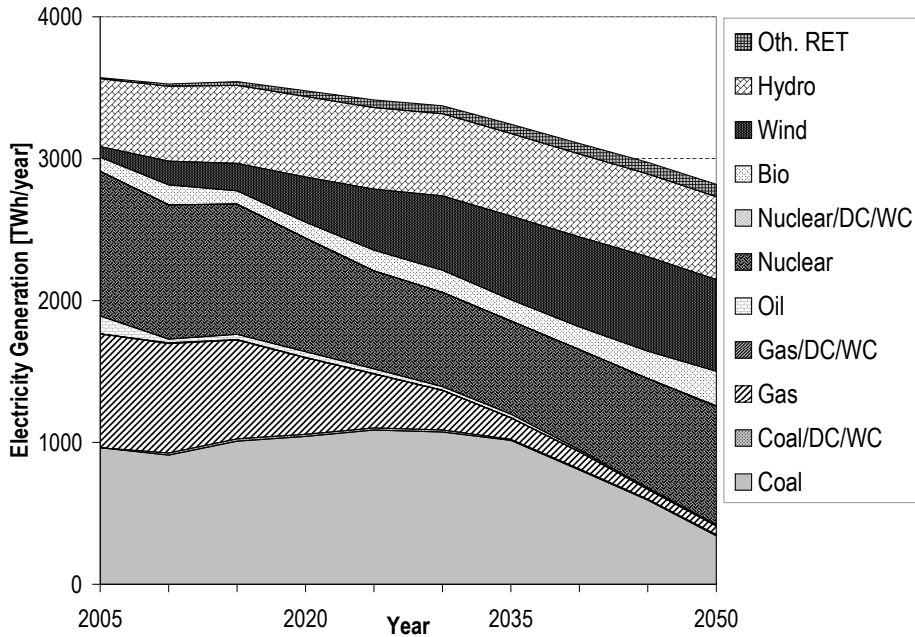
FIGURE 5.1.: *Electricity generation in the 450 ppm CO_2-eq mitigation scenario for EU27+2, with a maximum share of 30% wind power allowed in each region. The thermal technologies with advanced cooling systems (e.g. Coal/DC/WC) are part of the model solution within the tolerance of the solver, rather than explicitly needed due to model constraints.*

Major electricity generation technologies in 2050 are wind turbines on-shore with more than 230 GW installed while wind offshore capacities increase up to 43 GW in 2050. Hydro power contributes with approximately 200 GW installed to the total available generation capacity. Hydro power includes power generation from large and small (< 10 MW) hydro power plants. It is expected that the capacity of large hydro power plants can be increased by up to 8.5% until 2050, and small hydro power plants may see an increase of up to 40%, leading to 30 GW installed in 2050. In this analysis, hydro power was considered as a resource which will be exploited up to the maximum potential independent of the actual cost. The third largest contribution to total installed capacity is based on nuclear power, with 100 GW installed in 2050. However, this is equivalent to a

TABLE 5.2.: *Share of electricity generation per fuel type in relation to total generation in the 450 ppm scenario. Data is given for 4 European regions. The imports are defined as share of total demand while the export share is defined as exports per total generation of the specific region. Other renewable technologies (Oth. RET) comprise solar electricity, geothermal, tide and wave based electricity and biomass based generation. Fossil includes hard coal, lignite and natural gas based electricity.*

Region		North	South	East	West	EU27+2
Share hydro	2005	0.52	0.13	0.05	0.07	0.13
	2050	0.64	0.32	0.06	0.12	0.21
Share wind	2005	0.02	0.03	0.00	0.02	0.02
	2050	0.16	0.26	0.16	0.26	0.23
Share nuclear	2005	0.23	0.10	0.19	0.39	0.28
	2050	0.06	0.21	0.04	0.45	0.30
Share Fossil	2005	0.16	0.72	0.74	0.49	0.53
	2050	0.03	0.05	0.62	0.07	0.15
Share Oth. RET	2005	0.06	0.02	0.01	0.03	0.03
	2050	0.10	0.17	0.12	0.10	0.12
Share imports	2005	0.00	0.06	0.00	0.00	
	2050	0.00	0.30	0.00	0.00	
Share Exports	2005	0.03	0.00	0.07	0.01	
	2050	0.10	0.00	0.36	0.01	

reduction of nuclear capacity by 30%, compared to 2005. This reduction includes the policy dependent phase-out of nuclear power in some countries, such as Germany and Sweden.

Coal-fired power plants based on conventional technologies, as well as fossil based combined heat and power plants disappear from the system between 2035 and 2045, and only approximately 42 GW of advanced fossil based technologies (specifically, pressurized supercritical coal based power generation) will be in operation in 2050. All other technologies, such as biomass-based electricity generation, combined heat and power from various sources and solar generation technologies contribute by less than 5% to the total installed capacity in 2050. The installation of fossil generation equipped with CCS is only observed in the last two periods

of the time horizon, on a very low level. Less than 10 GW of generation capacity is equipped with CCS with most (80%) coal based CCS.

Additionally, in case of electricity generation, it is found that by using the MIP-solver (see section 3.3 for more information about MIP), large-scale technologies loose a share of total installed capacity of approximately 0.5% to 0.8% in the 450 ppm CO_2-eq scenario, compared to a solution from linear optimization. This is a relative small difference in case of already established technologies, but these results are indicating that the use of MIP is advantageous for transition periods in the energy system. One important aspect of finding accurate MIP solutions is the setting of the so called MIP-gap, which defines the tolerance between the objective value for the best node of the MIP analysis, compared to the MIP solution. By defining a small MIP-gap, the accuracy of results of the MIP-analysis is increased. If the MIP-gap is large, the solver of the equation system stops the optimization process, as soon as the tolerance level is reached and therefore, leaving solutions out which are describing the system more accurate. For all runs described in this dissertation, the MIP-gap is set to 0.015% of the objective value. It is expected that the importance of the MIP-feature increases, in case of the energy systems analysis of small regions and single countries, where specific investment decisions and other cost parameters have a higher influence on the objective value.

5.3.2. Electricity Trade

As already shown in section 4.7.2, the detailed representation of electricity trade in EuroMM is of high relevance. In this mitigation scenario, the electricity trade pattern changes compared to the baseline and the adaptation scenario. Mainly due to the reduction in electricity demand, the overall electricity flow across borders is reduced by approximately 18%, compared to the baseline in 2050, although the total electricity trade volume increases by a factor of 2.8 in the mitigation scenario, compared to 2005. In some regions (e.g. Italy and Germany), where the total amount of electricity traded is reduced compared to the baseline, imports from neighboring regions become more important, in terms of their overall share of trade flows. For example: In the baseline scenario, 43% of the

Italien electricity imports are generated in France, whereas in the mitigation scenario, this share increases to 84% in 2050 (see figure 5.2). Over the same time horizon, Italy reduces the imports of fossil based electricity from eastern Europe to less than 6% in the mitigation scenario, whereas in the baseline scenario, more than 35% of Italy's imports originate in that region.

This is not only due to the fact that in the mitigation scenario, CO$_2$-free electricity from mostly nuclear power needs to be imported from Italy, but merely due to limited technological potentials due to policy restrictions (e.g. restriction on nuclear investments), or limited resource availability in Italy. This regional constraints then limit the switch from fossil based generation to CO$_2$-free technologies and make electricity imports more competitive, compared to building up domestic generation capacity.

Further changes in trade flows were obtained in this scenario analysis. For instance, the reduction of electricity trade with Italy from eastern Europe is compensated by higher exports of electricity to Germany from Poland and the Czech Rep. This is due to the fact that eastern Europe is rich on hard coal reserves which emitt less CO$_2$, in case of burning it in power plants, compared to lignite as fuel source. Thus, in Germany, the production of lignite based power generation is reduced. The option of importing hard coal to Germany for power generation proves more costly in this analysis, as importing electricity from eastern Europe.
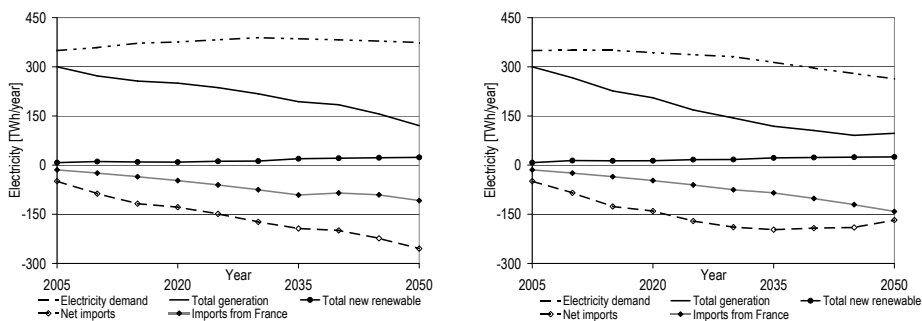
FIGURE 5.2.: *Electricity demand, generation and trade in Italy in the baseline (left figure) and the 450 ppm CO$_2$-eq scenario (right figure).*

5.3.3. Other Conversion Subsectors

Primary Energy

According to the shift in electricity generation from fossil sources to CO_2-free renewable and nuclear sources (see figure 5.1), and the higher efficiency of internal combustion engines in the transportation sector (Schade et al., 2009, chap. 9), the demand for fossil fuels decreases by approximately 34 EJ, from 64 EJ in 2005 to 30 EJ in 2050 (see figure 5.3), contributing by 33% to TPES in 2050. With 14 EJ, renewable sources contribute with a share of 27% to TPES in 2050, which corresponds to an increase of percentage points 20%, compared to 2005. Nuclear energy slightly increases its share from 14% to 18% in TPES from 2005 to 2050. Other fossil energy carriers, such as coal and natural gas, decrease their contribution to TPES by percentage points 10% each, to 7% and 14%, respectively. In this analysis, the energy conversion sector achieves emission reductions of approximately 75% compared to 2005, accounting for more than 55% of the total emission reduction, required from the energy sector (with the rest coming from reduced final energy demands and fuel switches in other sectors).

Low Temperature Heat

The demand for low temperature heat decreases by approximately 61% until 2050, and is mainly covered by biomass based generation. In 2050, 81% of LTH is either generated by biomass based CHP plants, or by burning of biomass in district heat plants. The remaining demand is covered by the use of coal in CHP plants. In EuroMM it is defined that the available potential for heat production based on waste (for the purpose of this analysis, waste products used for energy production are accounted as renewable sources), is fully used. As a result, heat from waste incineration contributes by more than 25% to the total heat output in 2050.

Fuel Production

In the 450 ppm CO_2-eq scenario, the demand for alternative fuels, such as hydrogen and biofuels for transportation, is assumed to be approx-
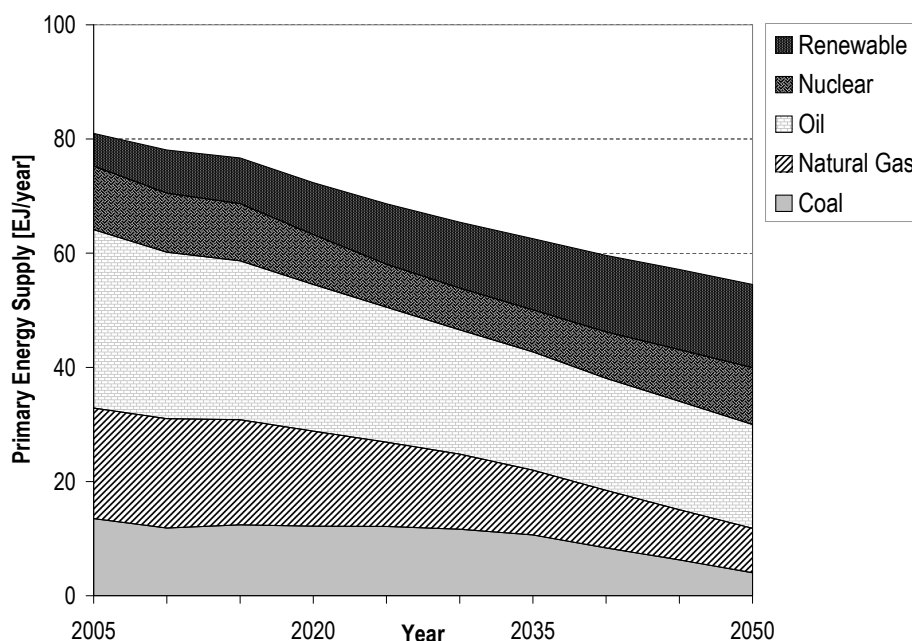
FIGURE 5.3.: *Primary energy supply in the 450 ppm CO$_2$-eq scenario.*

imately 70% higher, as compared to the baseline, covering a share of more than 10% of the total fuel demand for transportation. To satisfy this demand, total output of alternative fuels reaches 1.7 EJ in 2050, comprising 25% hydrogen (based on wind electrolysis and biomass gasification), and 75% biofuels from various sources (see figure 5.4). However, demand for biofuels consists mainly of biodiesel and ethanol. While in the early years of the modeled time horizon, biofuels are mainly produced from oil crops, the development of advanced technologies using wood and agricultural residues, brings a shift in production towards the end of the model horizon. Advanced biofuel technologies using cellulosic biomass and wood residues for fuel production are assumed to enter the market from 2020.

In the MIP-solution of the 450 ppm CO$_2$-eq mitigation scenario, hydrogen is mainly produced by electrolysis based on wind electricity and gasification of biomass (see figure 5.4). Large scale technologies, such as
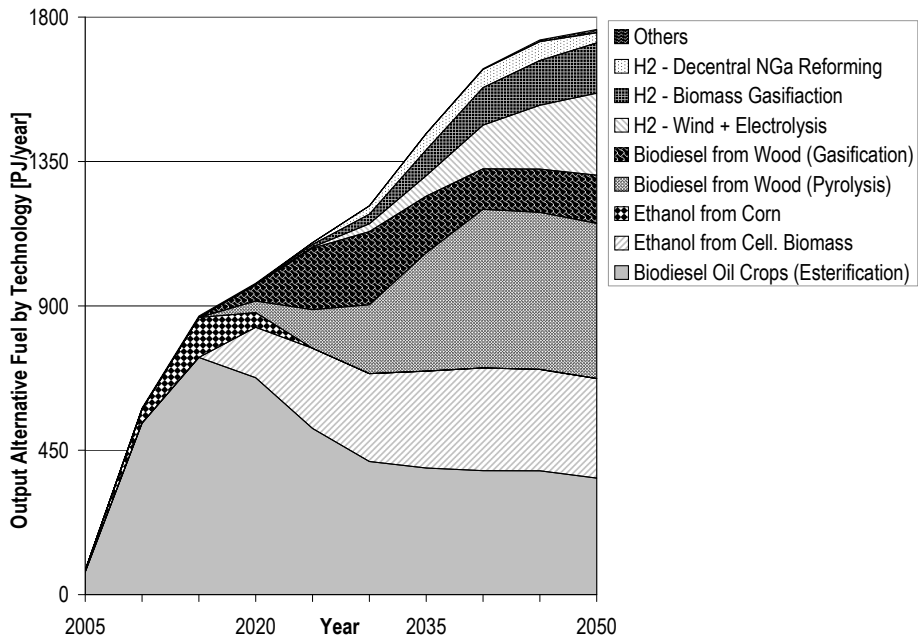
FIGURE 5.4.: *Alternative fuel production in the 450 ppm CO_2-eq scenario. H2 stands for Hydrogen.*

coal and nuclear based hydrogen production plants are not used due to the assumed lump-size, making these technologies not competitive with relatively costlier, small scale technologies. In the LP-version of the same scenario, coal and nuclear based hydrogen production is used from 2030 on, and these technologies increase their share up to 11% of total hydrogen production in 2050. However, it is unlikely that these technologies are used in small scales, as resulted from the LP-version of the scenario analysis. Therefore, the MIP solution is more accurate for depicting future scenarios, regarding transition technologies which are important for the introduction of new fuels in the energy system.

5.3.4. Economic Implications

To achieve the 450 ppm CO_2-eq mitigation scenario, cumulative investments in the energy conversion sector of around $1.5 trillion are needed

between 2005 and 2050. This is approximately 4%-5% below the level of the baseline scenario (see figure 5.5). The main drivers for these reduced investment requirements are the lower demands for final energy, as well as the availability of cost competitive generation of electricity based on renewable sources. The largest amount of investment is needed for the installation of wind turbines (30% of total cumulative investment in 2050), the refurbishment and upgrade of exisiting hydro power plants (18% of total cumulative investment in 2050), and the replacement of nuclear power plants (16% of total cumulative investment in 2050). The investment cost for the grid infrastructure is low (2%) mainly due to decreasing electricity demand, reducing the need for upgrading and extending transmission and distribution lines.

As compared to the baseline scenario, the cumulative discounted total system costs (the discounted total system cost includes all cost parameters defined in the model such as investment cost for technologies, fixed and variable operation and maintenance cost, transaction costs for trade flows as well as resource extraction cost within EU27+2.) for EU27+2 are 3% lower in the mitigation scenario, over the entire period (2005-2050), and reach \$4.1 trillion. Looking at the annual system costs in 2050, these are up to 33% below the expenditures as compared to the baseline. Further cost reductions are achieved due to lower imports of primary energy carriers. This reduces fuel import costs by 9% in 2050, compared to the baseline scenario. The overall cost reduction in the mitigation scenario is also owed to the fact that lower operation and maintenance costs can be achieved in terms of handling of primary energy carriers.

An important parameter in mitigation studies is the expected carbon price, defining how much it costs to emit one additional ton of CO_2. Given the CO_2 constraint in EuroMM for the 450 ppm CO_2-eq scenario, the marginal cost of CO_2 is estimated to reach approximately \$67 in 2050. This price is mainly influenced by the assumptions on future energy demand developments. This issue will be discussed in section 5.7 and further results are presented in the following chapter.
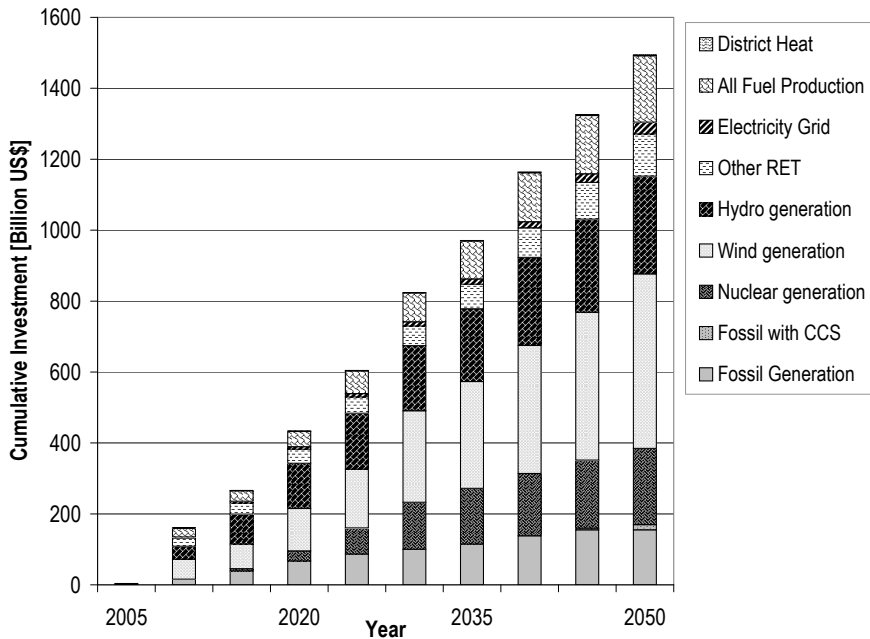
FIGURE 5.5.: *Cumulative investment costs per technology in the 450 ppm CO$_2$-eq scenario.*

5.4. Technological Choices

One of the challenges of replacing fossil-based power plants, particularly natural gas, is finding an alternative to provide peaking requirements. In the scenarios described here, peak electricity demand is supplied by hydro power plants with pumped storage and power plants using biogas, with some minor additional contributions from fossil generation. Peak requirements can also be managed by improving dispatch and reliability of renewable energy technologies through electricity grid connections between countries. In MARKAL it is specially foreseen that grid interlinkages contribute to the management of peaking demands (see equation MR_EPK in Loulou et al. (2004)). In EuroMM, it is assumed that enough capacity is installed (including grid interconnections) to cover the largest seasonal peak with a safety peak reserve margin of 30%. The reserve margin accounts for unexpected down time of equipment, and for some

uncertainty of the hydroelectric, solar and wind availability (Loulou et al., 2004).

Additionally, two constraints are further ensuring that paek demand can be met at all times in EuroMM. Firstly, the output of wind power was limited to 30% of total generation in this scenario, to reduce the uncertainty from intermittent sources. Secondly, the capacity of renewable technologies (including small hydro power, wind power and solar power), available for covering peak demand, was limited to 30% of the installed capacity of the specific technology (in MARKAL, the peaking constraint factor PEAK(CON) specifies the fraction of each capacity that is allowed to contribute to the peak load). In the further analyses (see chapter 6), the limitation of wind power will be removed since it is expected that in the future higher shares of intermittent sources can be managed within the grid infrastructure (Hoogwijk et al., 2007).

To achieve the climate target of stabilizing the temperature increase to less than 2 °C by 2100, the mere deployment of low-cost electricity generation technologies such as wind onshore is not sufficient. In this analysis additional capacity of renewable technologies is installed, including less mature technologies, such as solar photovoltaics and ocean energy (including tidal and wave energy), to meet climate targets although their total contribution to electricity generation remains small. These technologies are expected to experience further cost reductions and efficiency improvements, and are likely to become more relevant in the years after 2050, when further emission reductions are necessary. The competitiveness of all renewable energy technologies improves in particular in the mitigation case, as a result of rising prices for CO$_2$-allowances and stringent emission reduction targets.

5.5. Results for the 400 ppm CO$_2$-eq Scenario

5.5.1. Electricity Generation

Climate scientists are urging for stronger greenhouse gas emission reductions than these described in the 450 ppm CO$_2$-eq. The 400 ppm CO$_2$-eq constraint target corresponds to such stronger emission reduc-

tion efforts. By applying this constraint in EuroMM, the modeling results show, how further emission reductions can be realized. In this case, the electricity sector reduces its emissions by more than 90%, compared to the year 2005. This is a further reduction in CO_2 emissions from 530 Mt of CO_2 per year in 2050 in the 450 ppm CO_2-eq scenario, to less than 220 Mt of CO_2 per year in the scenario described here. By further reducing the output of coal and gas fired power plants to less than 3% in 2050 of total generation (see table 5.3), and by increasing the electricity output of CO_2-free technologies, this ambitious target can be met (see figure 5.6). The amount of fossil generation which needs to be replaced to achieve the target, is mainly provided by additional nuclear power. Renewable technologies based on biomass, solar, geothermal and ocean show a slight decrease of production, compared to the results shown in the 450 ppm CO_2-eq scenario, mainly since renewable generation in Nordic countries is replaced by nuclear generation. In other regions (East, West and South), renewable technologies increase their share in total generation compared to the 450 ppm CO_2-eq scenario until 2050 (see table 5.4). Again, gas powered generation proves to be too costly in this analysis, and is therefore not used for electricity generation by the end of the modeled time horizon, although the emissions per unit of electricity are lower, compared to coal fired generation (which is still used to a small extent). Additionally, further efficiency gains reduce the demand for electricity by 2% compared to the 450 ppm CO_2-eq scenario.

Looking at the different regions in more detail again, it is found that the countries with a potential for nuclear development increase their output of electricity, while regions with a high share of fossil generation reduce their output (see table 5.4). This scheme can be especially seen for eastern Europe. Compared to the 450 ppm CO_2-eq scenario, the output of electricity in eastern Europe drops by more than 30% until 2050. However, this decrase only occurs after 2035, when most of the power plants in place today reach the end of their technical lifetimes. Other regions, such as Scandianvia (SCA) increase their output of nuclear power by investing in additional capacity. Together with these changes in electricity generation, the trade flows accross borders change.
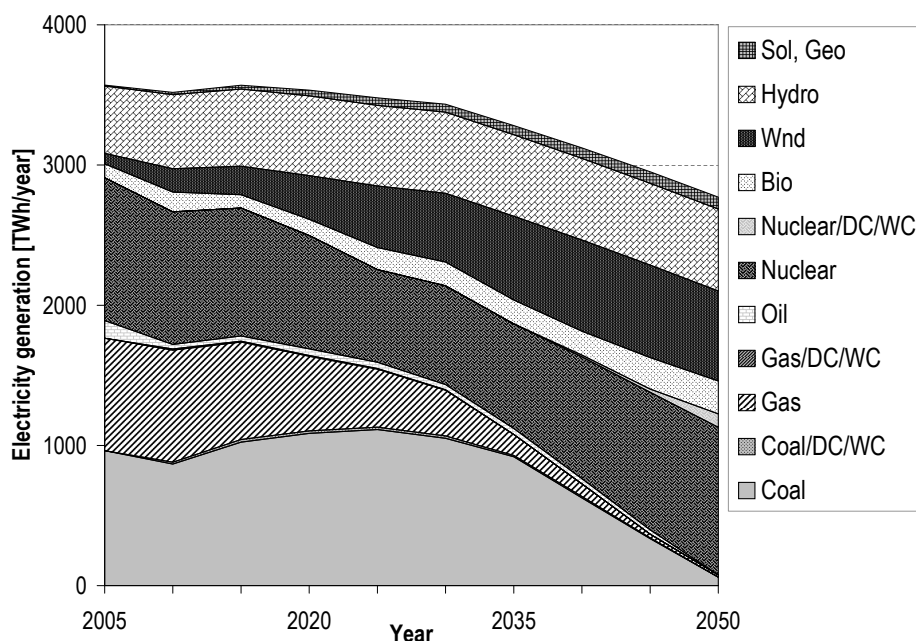
FIGURE 5.6.: *Electricity generation in the 400 ppm CO_2-eq mitigation scenario for EU29 with a maximum share of 30% wind power in the system. The thermal technologies with advanced cooling systems (e.g. Coal/DC/WC) are part of the model solution within the tolerance of the solver rather than explicitly needed due to model constraints.*

In comparison to the 450 ppm CO_2-eq scenario, no additional technologies contribute to the achievement of the climate target. The capacity of fossil generation with CCS only increases by 3.6 GW to 13.6 GW in 2050 whereas a slightly larger share of natural gas based generation is in operation. Technologies with the highest capacity installed again, are wind turbines, hydro power plants, and nuclear power plants. The capacity of nuclear power plants is approximately 30% higher, as compared to the 450 ppm CO_2-eq scenario.

TABLE 5.3.: *Share of electricity generation per fuel type in relation to total generation in the 400 ppm CO_2-eq scenario. Data is given for 4 European regions. The imports are given as share of total demand while the export share is defined as exports per total generation of the specific region. Other renewable technologies (Oth. RET) comprise solar electricity, geothermal, tide and wave based electricity and biomass based generation. Fossil includes hard coal, lignite and natural gas based electricity.*

Region		North	South	East	West	EU27+2
Share hydro	2005	0.52	0.13	0.05	0.07	0.13
	2050	0.57	0.30	0.08	0.11	0.20
Share wind	2005	0.02	0.03	0.00	0.02	0.02
	2050	0.18	0.23	0.21	0.25	0.25
Share nuclear	2005	0.23	0.10	0.19	0.39	0.28
	2050	0.14	0.27	0.33	0.51	0.40
Share Fossil	2005	0.16	0.72	0.74	0.49	0.53
	2050	0.01	0.01	0.19	0.01	0.03
Share Oth. RET	2005	0.06	0.02	0.01	0.03	0.03
	2050	0.07	0.17	0.18	0.09	0.11
Share imports	2005	0.00	0.06	0.00	0.00	
	2050	0.00	0.32	0.00	0.00	
Share Exports	2005	0.03	0.00	0.07	0.01	
	2050	0.27	0.00	0.13	0.06	

5.5.2. Electricity Trade

Due to the reduction of coal based electricity generation, eastern Europe decreases its output of power generation by 15% at the end of the model horizon, compared to 2005. To fully satisfy electricity demand, additional electricity is imported from Nordic countries. Although northern Europe is a net exporter of electricity in the 450 ppm CO_2-eq scenario, it imports electricity from eastern Europe in that specific scenario to satisfy peaking constraints. However, in the 400 ppm CO_2-eq scenario, this relation changes, and Nordic countries export electricity to eastern Europe (namely the Baltic's and Poland). Northern Europe is able to cover its own demand and increase its exports due to the installation of new nu-

TABLE 5.4.: *Comparison between the two mitigation scenarios. The difference in electricity generation is defined as output per technology in the 400 ppm CO_2-eq scenario, divided by the output per technology in the 450 ppm CO_2-eq scenario in 2050, minus 1. Positive values indicate an increase of output from the specific technology in the 400 ppm CO_2-eq scenario. Other renewable technologies (Oth. RET) comprise solar electricity, geothermal, tide and wave based electricity and biomass based generation. Fossil includes hard coal, lignite and natural gas based electricity.*

Difference		North	South	East	West	EU27+2
Share hydro	2005	-	-	-	-	
	2050	0.00	0.00	0.00	0.00	0.00
Share wind	2005	-	-	-	-	
	2050	0.26	-0.07	-0.11	0.00	0.13
Share nuclear	2005	-	-	-	-	
	2050	1.57	0.34	5.17	0.13	0.37
Share Fossil	2005	-	-	-	-	
	2050	-0.67	-0.80	-0.79	-0.92	-0.82
Share Oth. RET	2005	-	-	-	-	
	2050	-0.20	0.08	0.08	0.08	-0.03

clear power plants. This additional capacity increases total generation by 13% in 2050 compared to the 450 ppm CO_2-eq scenario.

Southern Europe slightly increases electricity imports by percentage points 2%, compared to the 450 ppm CO_2-eq scenario. Additional imports are mainly based on exports from western Europe.

5.5.3. Other Conversion Subsectors

Primary Energy

Based on the shift from fossil electricity generation to nuclear based generation (compared to the 450 ppm CO_2-eq scenario), the TPES for the fuels in focus changes accordingly. In this mitigation scenario, energy from coal is reduced to less than 3% of TPES. Additionally, the use of

natural gas is also reduced further, to less than 9% in 2050. Besides the increase of energy supply from nuclear sources, renewable energies also increase their share to levels above 30% in 2050.

Due to the reduction of demand for fossil sources in Europe, the imports of energy carriers such as crude oil and natural gas are reduced. In 2050, approximately 30 EJ of fossil sources and uranium are imported, compared to 70 EJ in 2005. Therefore, fuel imports of coal, oil, uranium and natural gas cover 60% of TPES in 2050. This is a reduction of more than percentage points 25% compared to the year 2005, where more than 85% of primary energy was supplied by fuel imports from these sources. The biomass imports (feedstocks) increase from 0.6 EJ in 2005 to 1.6 EJ in 2050.

However, not only the electricity sector reduces emissions further, but also other sectors contribute to meeting the target. In this analysis, the energy conversion sector achieves emission reductions of approximately 90% compared to 2005, accounting for more than 50% of the total emission reduction required from the energy sector (with the rest coming from reduced final energy demands and fuel switching in other sectors).

Fuel Production

As mentioned in section 5.2, EuroMM allows to model transport demand in the 400 ppm CO_2-eq scenario due to the implementation of additional demand technologies. As the results show (figure 5.8), additional demand for alternative fuels for transportation is generated in the 400 ppm CO_2-eq scenario. As an overall result, the demand for alternative fuels in this scenario is up to 40% higher in 2050, as compared to the 450 ppm CO_2-eq scenario. In total, almost all of the 2.5 EJ of this fuel demand is supplied by renewable sources. More than 85% is covered by liquid fuels based on biomass whereas less than 15% is hydrogen (based on wind and biomass).
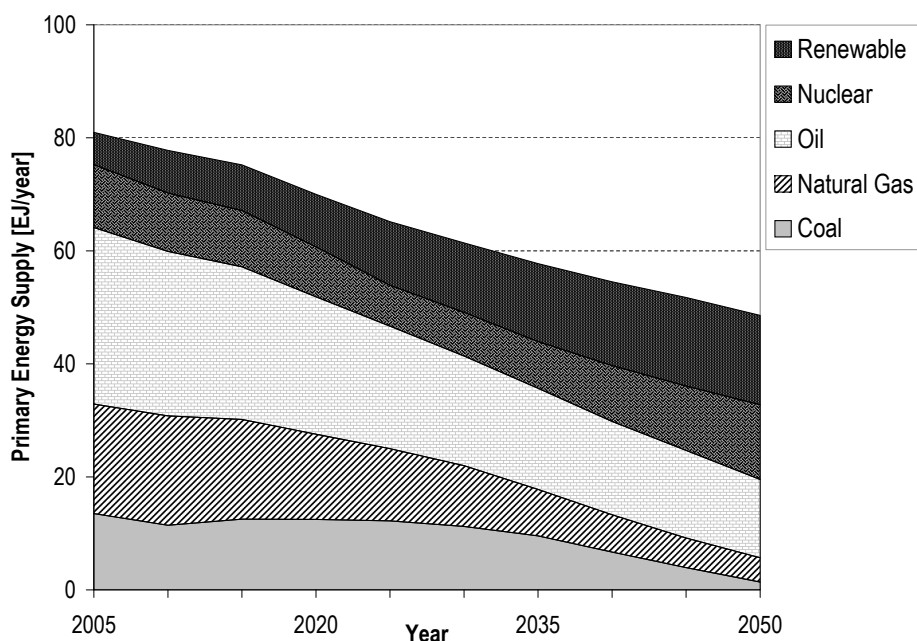
FIGURE 5.7.: *Primary energy supply in the 400 ppm CO$_2$-eq scenario. Coal includes hard coal and lignite resources, oil includes all oil products such as gasoline and diesel.*

5.5.4. Economic Implications

Due to the higher efforts needed in the energy conversion sector to achieve more stringent climate targets, the costs increase compared to the results presented earlier. However, the absolute cumulative investment in 2050 only differs by less than 0.5%, compared to the baseline results, where approximately $1.5 trillion are needed until 2050. Compared to the 450 ppm CO$_2$-eq scenario, additional investments are needed for nuclear power generation, biomass based power generation, and biofuel production. The cumulative discounted total system costs are approximately 4% higher in the 400 ppm CO$_2$-eq scenario as compared to the 450 ppm CO$_2$-eq scenario, due to mainly three relevant cost factors. Firstly, the cost for nuclear generation technology compared to coal fired power generation is higher due to the different cost structures (investment cost, fixed
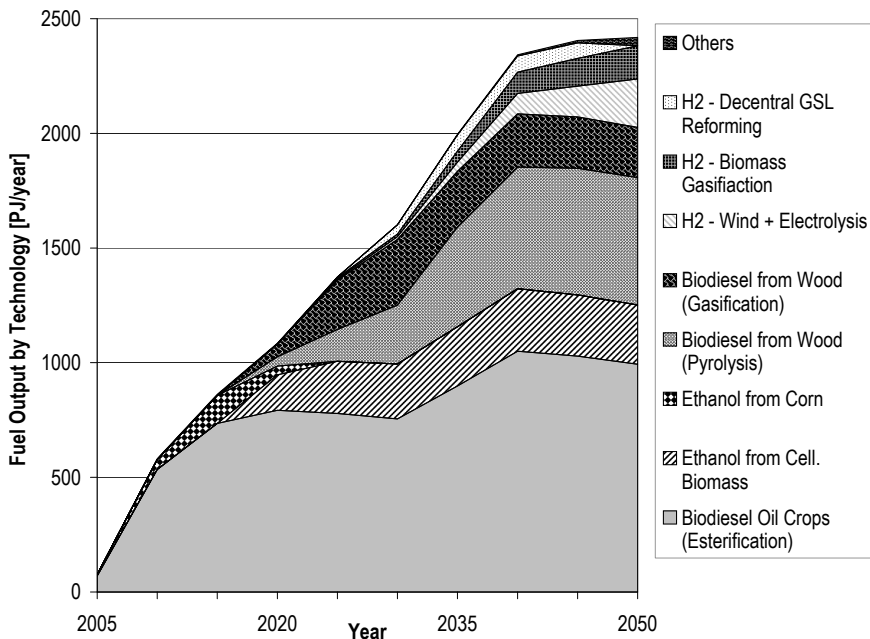
FIGURE 5.8.: *Alternative fuel production in the 400 ppm CO_2-eq scenario. H2 indicates the demand for hydrogen. Cell. Biomass indicates cellulosic biomass such as stover.*

operation and maintenance costs as well as variable operation and maintenance costs).

Secondly, the switch to alternative fuels (including biomass) with higher fuel costs for the feedstock as well as higher production costs, raises the overall system cost. Due to the limited resource potential of biomass for fuel production (e.g. oil crops and corn) in Europe, the additional biomass feedstocks need to be imported.

Thirdly, the total discounted system cost for additional CO_2-free electricity generation and fuel production would be higher in EU27+2 (approximately 16%), if not a part of the rising costs would be compensated by fossil fuel savings. Due to this fuel switch, the expenditure on fossil fuels is approximately 4% lower in the 400 ppm CO_2-eq mitigation scenario in 2050, as compared to the 450 ppm CO_2-eq scenario.

The marginal cost for CO_2 in this scenario increases to \$360 until 2050, and is therefore more than 5 times higher as compared to the 450 ppm CO_2-eq scenario. This high CO_2 price indicates the additional efforts are needed to achieve low emission targets.

5.6. Summary of Results

In this chapter it has been shown that climate change mitigation targets can be met, even in case of stringent emission reduction targets for relatively low additional or even reduced total system costs. However, a number of important changes are required in the energy conversion sector, to achieve the stringent mitigation targets explored in this analysis. These include an almost complete phase-out of CO_2 emitting fossil generation in Europe, a continued deployment of nuclear energy until 2050, and a large-scale deployment of renewables. Renewable electricity generation includes large contributions from wind and hydro power but also relies on technologies such as geothermal, ocean, biomass based and solar based electricity generation. Additionally, it is found that fossil generation with CCS is not cost competitive under the given set of assumptions.
Together with these changes in electricity generation, the electricity trade patterns between neighboring countries are also likely to change. Due to the geographically uneven distribution of renewable sources, relevant for CO_2-free electricity generation, these potentials are deployed in those regions where they are highest, and partly exported in form of electricity, if excess resources are available. This finding is more pronounced in the 400 ppm CO_2-eq climate target.

The production of alternative fuels such as biofuels and hydrogen is based on various technologies. At the end of the model horizon, biofuels are mainly based on cellulosic biomass and hydrogen is based on renewable sources. Especially in the case of hydrogen production, small scale technologies are favorable, to cover a relative small demand until 2050.

5.7. Discussion and Conclusion

The large-scale deployment of renewable energy technologies poses some challenges in terms of integrating large amounts of fluctuating power in the electricity grid, implying additional system costs. However, it is expected that it will be possible to cope with these challenges over the long-term, by reinforcing the grid infrastructure, and by expanding international transmission capacity, using back-up capacity, and through an expansion and better utilization of energy storage technologies (e.g. pumped storage of hydro power). The "smart grid" strategy of the European Union additionally supports the development of an advanced electricity grid, to cope with intermittent sources (European Commission, 2006a). Subsequently, one of the most important areas for policy intervention, to achieve cost-effective mitigation targets, may be in supporting open and efficient markets for electricity trade. This can be illustrated by the importance of trade for managing the large-scale deployment of renewables, and providing additional flexibility where countries have lower access to nuclear, hydroelectric or other CO_2-free generators that can be operated more or less on demand. Exploiting the renewable potentials in those regions where they are highest, together with unrestricted trade of electricity to areas[1] with high demand, is therefore essential. It is in the interest of the European countries to secure the electricity exchange across borders and among reliable partners. As a brief note, national concerns about security of supply are not considered directly in these results, but the approach adopted here is consistent with energy security within Europe as a whole.

Further important drivers for the model results are the assumptions on demand developments, and therefore expected efficiency improvements and related emission reductions on all levels of the energy chain. Major contributions to energy savings are assumed in the residential and services sector (Schade et al., 2009, chap. 6,7). Although the nec-

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[1]Although specific demand centers such as big cities are not modeled specifically in this analysis, it is of importance that enough transmission capacity is in place to connect large scale renewable generation pools (e.g. wind offshore) with centers where demand is high.

essary investments in efficiency improvements are not included in Eu-roMM directly, the results indicate that with the efficiency improvements, mitigation efforts are cost effective, even without accounting for avoided damages due to reduced climate change impacts. The monetarization of efficiency improvements are difficult to attribute to specific changes in appliances since new devices often incorporate additional functions and therefore cost increases of demand technologies can not be linked di-rectly to efficiency improvements (Schade et al., 2009, chap. 6,7). How-ever, additional investment cost in the residential and services sector for efficiency measures are estimated to be in the range of 45% to 80% of the realizable cost reductions in fuel spendings (Schade et al., 2009).

Given these exogenous demand assumptions in EuroMM, the relatively low CO_2 prices of \$67 in 2050, compared to other model scenarios ana-lyzing mitigation in the energy sector (Ruoss, 2009, Master Thesis) can be understood. By reducing demand for fossil fuels and electricity due to efficiency measures such as building codes in the residential sector, the installation of costly technologies with low CO_2 emissions can be avoided. However, there is a large uncertainty if these demand reductions can be achieved in the future and therefore further scenarios are analyzed (see section 6.2).

Additionally, it is important to notice that climate mitigation targets can not be met if not all energy sectors reduce greenhouse gas emissions in the future. This was found in first infeasible model runs, which included relatively stable greenhouse gas emissions from final energy demand sectors, such as the transportation sector. In those analyses, the emis-sions reductions from the electricity sector were not sufficient to achieve climate targets. Therefore, it is mandatory to achieve additional emission reductions outside the electricity and fuel conversion sector.

Maintaining and expanding the deployment of nuclear energy will likely require a different type of policy support to address concerns regarding waste disposal, risk of accidents and nuclear proliferation as well as guar-anteeing security of investments thus ensuring sufficient public support. The phase-out of CO_2 emitting fossil generation will be brought forward

by high and stable CO_2 prices which are likely to be achieved by CO_2 taxes or cap and trade systems.

The use of the mixed integer feature (MIP) in the scenario analysis is important regarding two characteristics of the energy system. In the future, it is expected that new technologies are available to cover demands of alternative fuels such as hydrogen or biofuels. In this case, small scale technologies (e.g. hydrogen based on wind with electrolysis) are more attractive since they can be more easily deployed to cover small initial fuel demands, as compared to large scale technologies, which are only competitive in case of large demands. In this setup, the introduction of mixed integer problems can help to identify key technologies, which are suited to initial niche markets, paving the way for large scale technologies necessary, to cover rapidly growing demands in the future. If a minimum block-size capacity which needs to be installed in a certain region is not defined for large scale technologies, these technologies would be deployed earlier and therefore model results would be less reliable for explaining transition periods in the energy system.

In case of electricity generation, potentials for the development of small scale technologies are generally underestimated in solutions based on purely linear algorithms. This can be explained as follows: if the model allows technologies which are installed in reality as large power plants to be deployed in small units, small scale technologies are excluded from the model solution since they lack their specific advantage. By including technologies with a lump size, the higher cost of installing small scale technologies is compensated by the higher flexibility of installing small units to efficiently cover demands without overproduction. This finding can be demonstrated by the reduced installation of large scale technologies for electricity generation in the 450 ppm CO_2-eq scenario.
This finding is of additional importance where endogenous technical learning (not included in the scenario analyses described in this dissertation) is integrated in the model analysis. Using such feature, small scale technologies would benefit more from learning effects due to earlier installed generation capacity. Under specific conditions it might be possible that large scale technologies do not enter the system, since small scale tech-

nologies profit from these early learning effects, and therefore, are more competitive in the long run, compared to large scale technologies.

The results presented in this chapter represent only two of many different possible pathways for a potential low carbon future, and other scenarios are further described in the following chapter.
However, to achieve a global 400 ppm CO_2-eq target in 2100, further efforts are needed to continuously reduce emissions from the energy system. According to studies also conducted in the ADAM project and soft linked to the results presented here, very low emissions or even negative emissions are required to stay below a climate warming of plus 2 °C (Edenhofer et al., 2009). In this dissertation, the electricity sector is targeted as a first sector, to reduce emissions in a cost effective way up to 2050, and reduces emissions by approximately 90% under stringent climate targets. To achieve further emission reductions in the longer term, it is expected that other energy conversion e.g. hydrogen- and biofuel production, as well as CO_2-free electricity for transportation is of increasing interest. The extension of the model in the transportation sector is important for analyses which are used to investigate scenarios reaching beyond the considered model horizon.

6. Technology & Policy Constraints

6.1. Introduction

As introduced in chapter 3 and 5, uncertainties exist regarding model assumptions and results, relevant for decision makers which want to draw conclusions from the scenario analyses, described in this dissertation. Uncertainties exist regarding future electricity demand projections based on efficiency improvements in the residential and services sector, as well as uncertainties about the availability of technologies which could be important in the future, for achieving stringent emission reduction targets.

It is the aim of this chapter, to analyze the major uncertainties which were found in the course of this dissertation, and to identify robust technology choices for climate change mitigation in the energy conversion sector. Due to this analysis, areas are identified, where uncertainty can be reduced, leading to advices where technology support needs to be improved by decision makers.

In this scenario analysis, four key parameters were selected to further analyze the European energy conversion sector. Firstly, the uncertainty of efficiency gains in the final energy demand sectors, as assumed and described in chapter 5, is addressed. Therefore, a set of model runs is performed, using higher electricity demand estimates for the services and residential sector.
Secondly, it is uncertain, how much intermittent sources can be integrated in the energy infrastructure, to guarantee stable grid operation and security of supply. In the analyses introduced in the chapters 4 and 5, the output of wind power was limited to 30% of total generation in each region, to reflect a lower limit, expected to be feasible in the near future. However, wind power is projected to be one of the major sources for emission free

electricity generation in the future and therefore special interest is given to the analysis of its potentials for electricity generation. In a set of model runs the limitation of wind power to 30% of total generation is stepwise removed, allowing for wind power contributions of up to 50%, to cover electricity demand. The results are introduced in section 6.3 for low and high electricity demand scenarios.

Thirdly and fourthly, since the availability and public acceptance of CO_2-free, large scale technologies for electricity generation is under debate, possible limitations to nuclear power and fossil generation with CCS were analyzed. By limiting investments in new nuclear capacity and in an additional step, limiting the availability of CCS technologies, it is analyzed, how the energy conversion system changes, if one or more CO_2-free options are excluded from the set of technologies available.

An overview of the different scenarios is given in table 6.1. However, due to the large amount of data, generated in these scenarios, only major findings related to the electricity sector are introduced in this chapter.

6.2. The Uncertainty of Efficiency Gains

6.2.1. Inputs and Assumptions

The exogenous assumptions for electricity demand in the residential and services sector (Schade et al., 2009, chap. 6,7) are new in the way that no other scenarios were found in literature, forecasting a similar trend in electricity demand. Therefore, it remains uncertain, if such efficiency gains can be achieved in the future.

To investigate the impact of the demand estimates on the electricity generation sector, the scenarios MIT2 and MITB were set up, assuming higher electricity demand in the residential and services sector. To do so, the modeler assumed, that the given efficiency increase for the residential and services sector (Schade et al., 2009, chap. 6,7), overestimates the likely demand reductions by 5% per 5 years, over the considered time horizon. By applying these higher estimates, an overall increase of electricity demand by approximately 35% in the MIT2 scenario, compared to

TABLE 6.1.: *Overview of main model constraints (technological and policy constraints), analyzed for the potential influences on the results derived from the unconstrained mitigation scenarios of the 450 ppm CO_2-eq scenario (MIT1) and the 400 ppm CO_2-eq scenario (MITA). The scenarios MIT1 and MITA are introduced and discussed in chapter 5.*

Scenario	450 ppm CO_2-eq	400 ppm CO_2-eq	Wind- potential	Demand	No new nuclear	No CCS
MIT1	x	-	30%	-	-	-
MIT2	x	-	30%	high	-	-
MIT3	x	-	40%	-	-	-
MIT4	x	-	40%	high	-	-
MIT5	x	-	50%	-	-	-
MIT6	x	-	50%	high	-	-
MIT7	x	-	30%	-	x	-
MIT8	x	-	30%	high	x	-
MIT9	x	-	30%	-	x	x
MIT0	x	-	30%	high	x	x
MITA	-	x	30%	-	-	-
MITB	-	x	30%	high	-	-
MITC	-	x	40%	-	-	-
MITD	-	x	40%	high	-	-
MITE	-	x	50%	-	-	-
MITF	-	x	50%	high	-	-
MITG	-	x	30%	-	x	-
MITH	-	x	30%	high	x	-
MITJ	-	x	30%	-	x	x
MITK	-	x	30%	high	x	x

the MIT1 scenario, and an overall increase of approximately 50% in the MITB scenario, compared to the MITA scenario, is obtained. No other changes regarding availability factors, growth factors for electricity generation technologies, and climate targets were implied in the scenarios MIT2 and MITB, compared to the scenarios MIT1 and MITA, respectively.

6.2.2. Results

Given the higher electricity demand from the residential and services sector, additional electricity generation is needed. In figure 6.1 the results for electricity generation are given for the scenarios MIT2 and MITB, respectively.

Compared to the mitigation scenarios with lower electricity demand (see figure 5.1 and figure 5.6), additional nuclear power as well as a slight increase of wind power generation is found to cover additional electricity demand in both mitigation scenarios (see figure 6.1, (a) and (b), for the high electricity demand scenarios). All other electricity generation technologies do not increase their overall output significantly, indicating that nuclear power is the most cost competitive option under the given set of assumptions.

Due to the higher electricity demand, the marginal cost of CO_2, as reported in section 5.3.4 increases from \$67 to above \$85 in 2050, in the 450 ppm CO_2-eq scenario and from \$360 to approximately \$460 in 2050, in the 400 ppm CO_2-eq scenario. Total investment cost in electricity generation capacity for both scenarios with high electricity demand are approximately 20% to 30% higher, as compared to the scenarios MIT1 and MITA. The total discounted system cost (including costs of fuel imports) are 3.1% higher in the scenario MIT2 and 4.4% higher in the scenario MITB compared to the respective mitigation scenario with lower demand.

(a) 450 ppm CO_2-eq scenario, MIT2   (b) 400 ppm CO_2-eq scenario, MITB
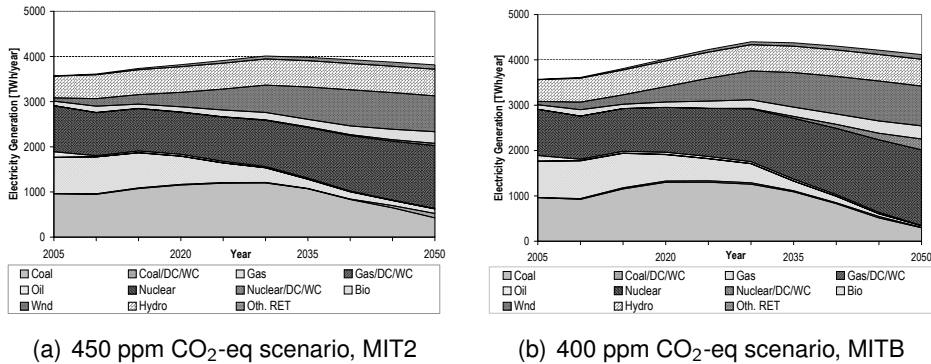
FIGURE 6.1.: *Electricity generation for the MIT2 (a) and the MITB (b) scenario for EU27+2 considering different mitigation targets under higher final electricity demand assumptions. The thermal technologies with advanced cooling systems (e.g. Coal/DC/WC) are part of the model solution within the tolerance of the solver rather than explicitly needed due to model constraints.*

6.3. The Potential of Wind

6.3.1. Inputs and Assumptions

Based on the estimates for wind power potentials described in section 3.3.3, wind power generation in Europe is estimated to approximately 1200 TWh in 2050 for the mitigation scenarios. Countries with the highest potential for wind power (including onshore and offshore potentials) are France and United Kingdom with 224 TWh and 216 TWh, respectively. However, these potentials can not be fully exploited if technical constraints of connecting intermittent sources and especially wind power with conventional grids, limit the installation of additional wind capacity.

Mainly two different characteristics of wind power are regarded as limiting factors for large scale wind integration in the power network. On the one hand, technical constraints such as different designs of wind turbines (e.g. variable speed turbine versus fixed speed turbine design) influence the power quality, which may cause voltage collapse problems (Ackermann and Söder, 2002; Akhmatov, 2006), in case of high penetration of

wind power in the network. In this dissertation, these kind of constraints were not considered since different technology designs were not available in the model. However, it is expected that such problems can be resolved in the future, since technical solutions are likely to be available (Ackermann and Söder, 2002).

On the other hand, the availability of wind fluctuates over different time periods, from short term wind speed changes, to yearly average changes. To account for the difficulties described here, to integrate large shares of wind power in the network, the maximal contribution of wind power to total generation was limited to 30% in the scenarios described in chapter 4 and 5. However, as also described previously (Ackermann and Söder, 2002; Akhmatov and Knudsen, 2002), plans exist for e.g. Denmark, to increase wind capacity in the coming decades, to contribute by 40% - 50% to total electricity generation. Therefore, the limitation of wind penetration of 30% is relaxed in steps of 10% up to 50%, in the scenarios described here (runs MIT3 to MIT6 and MITC to MITF).

To ensure that enough electricity can be provided at any time under consideration of high wind power penetration, the following two parameters were used:

The reserve capacity is set to 30% of total installed capacity to force the model to invest in additional backup capacity to compensate for possible shortfalls of intermittent sources. Additionally, the contribution of intermittent sources to peak electricity generation is limited to 30% of the installed capacity (e.g. if 3 GW of a certain intermittent technology are installed in one region, only 1 GW is allowed to contribute to cover electricity demand at peak time).

To cope with general changes in wind power availability, EuroMM includes the option of electricity storage, e.g. in form of hydro power in pumped storage systems which potentially could take up excess of wind power in case of low demand, and could contribute as backup capacity in case of low wind periods. To actually use pumped storage systems in connection with fluctuating wind power, the pumps would need different operation structures today, to be used as storage and backup capacity. Nowadays, pumped storage capacity is mainly used for providing peak electricity rather than backup capacity and is often linked to base load

generation. In EuroMM, the option of pumped storage technologies is given for countries where this technology exists today.

Furthermore, the wind technologies are defined as externally load managed in EuroMM, and the output of this technology is calculated on the basis of installed capacity and the capacity factor in each season, rather than based on annual availability factors for conventional technologies (see Loulou et al. (2004) for further explanation of externally load managed technologies). Therefore, the model has limited flexibility to operate the wind turbines in times where demand is highest.

6.3.2. Results

Under the given set of assumptions for peaking constraints, reserve capacity and capacity factors for wind power, the results of the scenarios MIT3 to MIT6 and MITC to MITF indicate that large amounts of wind power can be integrated in the electricity sector, to cover final electricity demand (see figure 6.2 for the results of the 450 ppm CO_2-eq scenario).

In case, where additional wind resources are available, the results for the model runs further indicate that wind power is cost competitive, compared to established power generation technologies (see figure 6.3). By removing the bounds on wind penetration, the output of wind power could be increased by up to 380 TWh in 2050, comparing the runs MIT1 and MIT5. This is equivalent to a growth of more than 58% in wind power output between those scenarios. Under more stringent climate targets additional 246 TWh could be generated by wind turbines.

Depending on the mitigation target, and electricity demand scenario, wind power mainly competes with nuclear power and coal based power generation. By increasing the share of wind power from 30% to 40% in the scenarios with lower electricity demand, mainly nuclear power is replaced (MIT1 versus MIT3). This is due to the fact that Southern Europe and especially Spain increases its output of wind power, and is therefore less dependent of CO_2-free electricity imports from France. Therefore, France reduces the output of nuclear power. Additionally, in Great Britain, wind power replaces nuclear generation since wind power is more com-
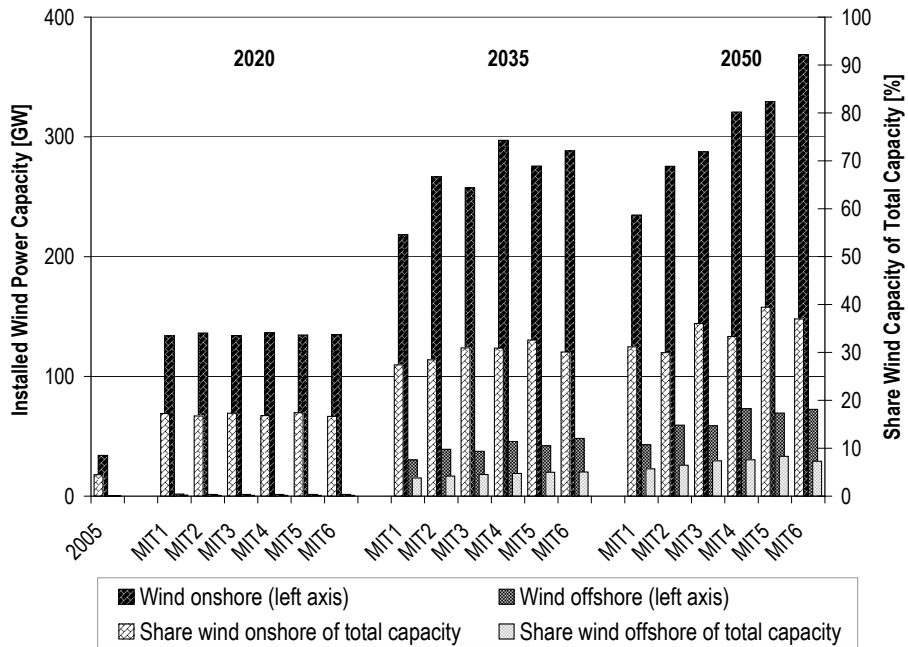
FIGURE 6.2.: *Installed wind power capacity for onshore and offshore technologies in the 450 ppm CO_2-eq mitigation scenario considering different levels of wind power penetration and final energy demand (Scenarios MIT1 to MIT6 as described in table 6.1). The right axis indicates the share of wind power capacity in total installed capacity for electricity generation.*

petitive in case of high penetration allowance. If the wind power penetration is set to the maximum of 50%, wind power is further replacing nuclear power due to the reasons mentioned above. The reduction in fossil generation mainly takes place in eastern Europe, which decreases exports to northern Europe due to higher availability of wind power in Scandinavia.

Comparing the scenario with higher electricity demand (MIT2) with the scenario of lower electricity demand (MIT1), it is found that all CO_2-free technologies increase production, to achieve the climate target. In the scenarios with higher electricity demand and higher penetration of wind power (MIT4 and MIT6), nuclear power as well as fossil generation are reduced, compared to scenario MIT2. However, the regional electricity

(a) 450 ppm CO$_2$-eq scenario

(b) 400 ppm CO$_2$-eq scenario
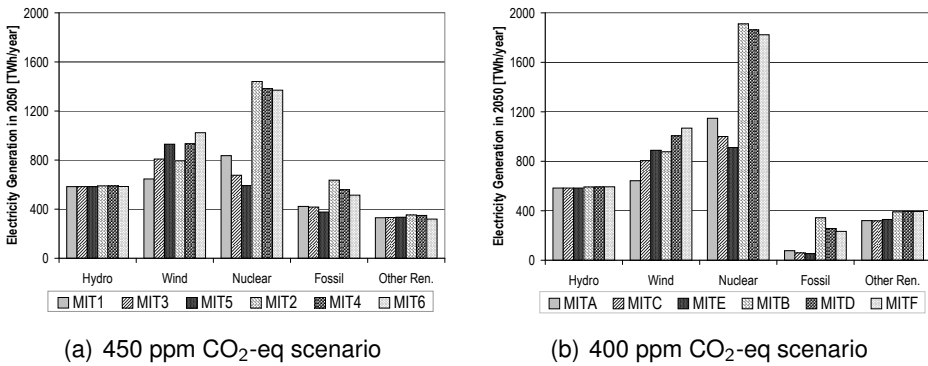
FIGURE 6.3.: *Electricity generation in the year 2050 from the various technologies available, comparing the set of different mitigation scenarios MIT1 to MIT6 (a) and MITA to MITF (b) for EU27+2 which analyze the potential of wind power under different levels of final electricity demand. See table 6.1 for scenario specifications.*

generation pattern is different, as compared to the scenarios with low electricity demand. Wind power is again replacing fossil generation in southern Europe, but France is not reducing output of nuclear generation. Instead, France is shifting electricity exports to Italy via Switzerland since Italy does not have additional CO$_2$-free resources available. However, in other regions such as Great Britain or Germany, wind power replaces fossil generation, often equipped with CCS, in case of high demand scenarios.

In the 400 ppm CO$_2$-eq scenario with lower electricity demand, the output of fossil generation is generally low due to the stringent climate target and therefore, higher allowance for wind power mainly replaces output of nuclear generation (scenarios MITC and MITE). In the scenarios with higher electricity demand and higher contribution of fossil based generation with CCS (MITD and MITF), wind power replaces coal based power generation to a higher extent in the first place, and nuclear power to a smaller extent, similar to the results of the scenarios with lower electricity demand.

For all scenarios it is found that wind power does not replace other renewable electricity generation, despite their generally higher cost. The main reasons for this is that only few countries have a high potential for wind power available, which could contribute by more than 30% to power generation. These countries or country aggregations are namely Great Britain, France, Spain and Portugal (IBE), and Denmark. All other regions in Europe rely on domestic renewable sources, to comply with the climate targets.

In economic terms, the higher penetration of wind power is favorable since the import of fuels such as coal and uranium to Europe from the rest of the world can be reduced. This fuel reduction and the related shift in the cost structure of electricity generation (especially the reduction of fixed as well as variable operation and maintenance cost) overcompensates the higher investment cost of wind power capacity (see appendix C for cost comparison of the different electricity generation technologies).

Additionally, it is found that due to the limited number of seasons and the limitation of storing electricity across seasons in the model, the pumped storage capacity is hardly used as backup for intermittent sources in EuroMM.

6.4. Restriction of Nuclear Power

6.4.1. Inputs and Assumptions

A further set of analyses was undertaken to show implications, when different nuclear policies are applied on European level. Due to different policy restrictions, regulatory concerns and unfavorable economic conditions, it remains open to which extent nuclear technology will be available in the future. On the one hand policy makers and people of many countries are undecided if nuclear technologies should be available in the electricity generation portfolio. Contributing to this abeyance in people's opinion are unresolved questions about nuclear waste disposal, nuclear proliferation and additionally, different risk perceptions of probabilities of nuclear accidents. This high level of uncertainty and divergence in public

opinion means that political support may change which creates adverse parameters for investments in new generation capacity in some European countries (e.g. Belgium, Sweden, Germany among others). Due to these conditions, investments in new nuclear capacity in those regions are currently small. On the other hand, regions with higher affinities for nuclear generation (e.g. France and Finland) do invest in new generation technology. However, only two construction sites are open for building new nuclear capacity in Europe in 2009, and both projects face difficulties in financial terms, as well as difficulties in finishing within the projected installation time. These difficulties are mainly linked to the development of new types of nuclear reactors, which are expected to be resolved in future projects. However, the financial and administrative support of governments is crucial to successfully install these new nuclear projects. As shown in the scenarios MIT1 and MITA, additional nuclear generation is expected to play an important role in mitigation from 2015 on. The projected installations of new nuclear capacity in the 450 ppm CO_2-eq scenario show 3.2 GW of new capacity on line in 2015 and additional 9.6 GW on line in 2020. With the more stringent climate targets, 2.4 GW and 12 GW would need to go on line in the respective periods, indicating higher investment needs for nuclear power in the later periods.

To analyze the different implications of country-specific nuclear policies, the wide range of possible solutions was confined by the given mitigation scenarios MIT1 and MITA, where the investment in nuclear was relatively open, for most of the European countries and the additional scenarios MIT7 and MIT8 as well as MITG and MITH (see table 6.1 for further specifications), where no investments are allowed in new nuclear capacity. Additional to the restrictions in new nuclear investments, the share of wind power within the network is limited to 30% of total electricity output. Although it is unlikely today that no new nuclear investments are realized in the future in Europe, the introduced scenarios are used to analyze cost implications and changes in electricity trade, if this specific technology is excluded from achieving stringent greenhouse gas emission reductions.

6.4.2. Results

Electricity Generation

In this scenario analysis it is found that both climate change mitigation targets can be met in 2050, if the investment in new nuclear generation is restricted. However, this limitation in nuclear availability leads to important changes in the electricity generation sector. Under the assumption of limited availability of wind power, as a cost-competitive alternative for CO_2-free electricity generation, the replacement of nuclear power in the scenarios MIT7, MIT8, MITG and MITH is based on fossil generation, equipped with CCS. In case of more stringent climate targets and low electricity demand (case MITG), the share of fossil generation with CCS is higher as compared to the 450 ppm CO_2-eq scenario (see figure 6.4 and table 6.2).

The coal-based technologies (including pressurized coal supercritical with CCS, integrated coal gasification with combined cycle with CCS and gas powered gas turbines in combined cycle with CCS) appear to be more cost competitive compared to some of the other alternatives, such as renewable energy technologies. In case of high electricity demand and limited availability of wind power, CCS would need to be available from 2020 on, in large scales (run MITH, 400 ppm CO_2-eq scenario). In the two periods 2020 and 2025, approximately 19 GW of coal based power generation with CCS need to be installed in the MITH scenario. In addition, fossil based CCS technologies account for up to 25% of total installed capacity, adding up to approximately 270 GW in 2050. Therefore, almost 100% of the installed fossil capacity would be equipped with CCS (see table 6.2). In case of less stringent climate targets or lower electricity demand in 2050, the share of CCS technologies compared to total installed capacity is at least 15% equivalent to 115 GW installed.
To achieve these growth rates in CCS technologies, it is essential that the required CO_2-storage sites are established in the same time. In scenario MITH, up to 29 Gt of CO_2 need to be stored in underground reservoirs, mostly for CO_2 from coal-fired generation (95% of total storage). Since it is unlikely that captured emissions are transported accross borders, the largest reservoirs are needed for France and the region GBI with ap-

(a) 450 ppm CO$_2$-eq Scenario MIT7

(b) 400 ppm CO$_2$-eq Scenario MITG

(c) 450 ppm CO$_2$-eq Scenario MIT1

(d) 400 ppm CO$_2$-eq Scenario MITA
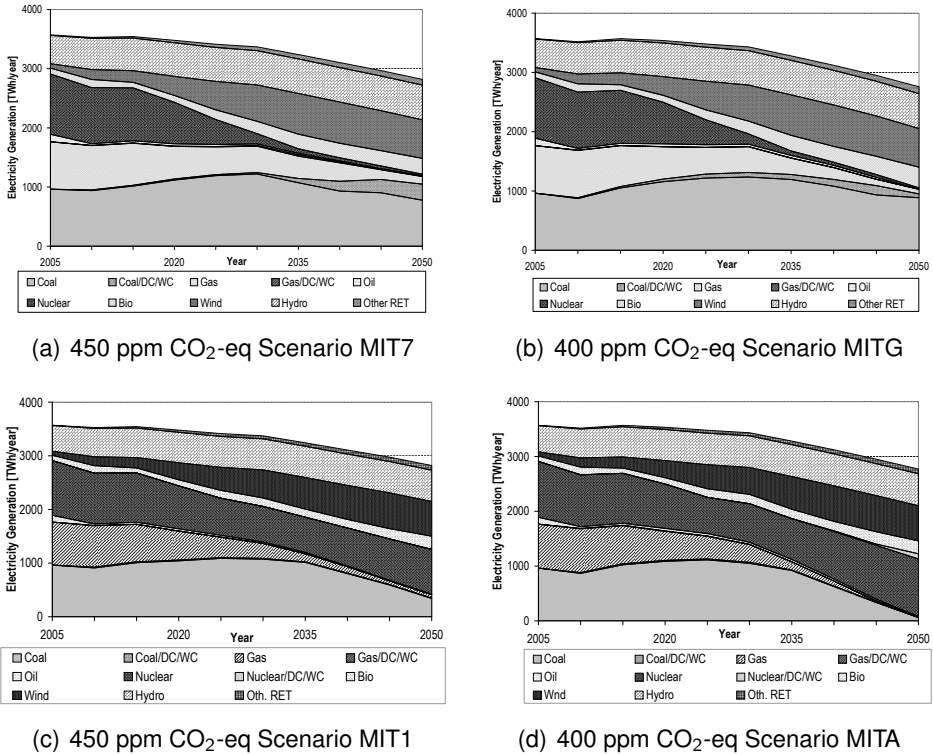
FIGURE 6.4.: *Electricity generation in EU27+2 in case that no investment in new nuclear capacity is allowed during the modeled time horizon under two different mitigation scenarios (450 ppm CO$_2$-eq, run MIT7, (a) and 400 ppm CO$_2$-eq, run MITG, (b)). The high contribution of coal based generation with advanced cooling technologies is based on the definition of the coal based IGCC technology with CCS which is specified as technology only available with advanced cooling (Goldstein et al., 2002). For comparison reasons, the results from the scenarios MIT1 and MITA for electricity generation are given in sub-figure (c) and (d), respectively. See section 5.3 and 5.5 for further explanations on the results of the scenarios MIT1 and MITA.*

TABLE **6.2.:** *Installed fossil electricity generation capacity equipped with carbon capture and sequestration. The technologies described are "pressurized coal supercritical generation" (Coal pres.), "gas powered gas turbine in combined cycle" (NGCC + CCS) and "integrated coal gasification with combined cycle" (IGCC + CCS). The total share is compared to the total installed electricity generation capacity in 2050 while "Share Fossil" refers to the share of fossil generation capacity with CCS compared to total fossil generation capacity.*

	Coal pres. [GW] 2050	NGCC + CCS [GW] 2050	IGCC + CCS [GW] 2050	Share Total [-] 2050	Share Fossil [-] 2050
MIT7	79	0	36	0.16	0.59
MIT8	127	2	74	0.21	0.70
MITG	119	18	16	0.20	0.82
MITH	212	40	15	0.25	0.96

proximately 5 Gt and 4.2 Gt capacity for CO_2, respectively. As published previously (Christensen and Holloway, 2004; Odenberger et al., 2008), the nowadays recognized reservoirs are large enough, to take up the captured emissions presented here. The largest reservoirs are identified offshore in the North Sea in depleted oil and gas fields (Christensen and Holloway, 2004; Odenberger et al., 2008). Additional reservoirs were found in the North German basin, and in the Paris basin (Christensen and Holloway, 2004; Odenberger et al., 2008). However, no details about CO_2 reservoir capacity and CO_2 transportation infrastructure were included in this dissertation.

Electricity Trade

Due to the reduction in available nuclear generation capacity, the trade pattern for all 4 scenarios changed, compared to the related scenarios, in which investments in nuclear technologies were allowed. The total trade volume for EU27+2 changes between approximately 0% (MITG vs. MITA) and more than 31% (MITH vs. MITB) until 2050. These differences are highly dependent on the region-specific trade flows, which in some cases

change significantly. This is further explained in the following for western Europe, with the highest share of nuclear generation in the MITA scenario. In the comparison between run MITG and MITA, western Europe partly replaces nuclear generation by fossil generation based on coal and gas with CCS. This means that by 2050, approximately 780 TWh of nuclear based electricity generation are replaced by 500 TWh of fossil based generation with CCS and a slightly higher output of RET (+25 TWh in 2050). Additionally, western Europe switches from a net exporter of electricity (98 TWh in MITA) to a net importer of electricity (103 TWh in MITG). This change in electricity output in western Europe then influences electricity generation in other regions such as eastern Europe. Due to the availability of large coal reserves and the potential for coal based generation with CCS, eastern Europe expands generation until 2050. However, a large share of this expansion (+47% in total generation compared to MITA) is exported to other parts of Europe. On the one hand, exports to southern Europe are increased, including trade routes via additional neighboring regions (e.g. trade from CZSL to ITA via AUT and Hungary and Slovenia), while on the other hand, electricity exports to western Europe (e.g. Germany) are increased even further, compared to the results presented for the MITA scenario.

In the scenario with high electricity demand and stringent climate targets (MITH vs. MITB), all regions need to invest in additional fossil generation capacity with CCS, to cover final energy demand and therefore, electricity trade reduces. While in scenario MITB, a share of the growing electricity demand for southern Europe is covered by additional generation of nuclear electricity in western Europe, this option is not available in scenario MITH. Therefore, southern Europe installs gas and coal based generation capacity with CCS, to cover higher electricity demands. Additionally, the option of increasing electricity imports from eastern Europe, as seen in the scenario MITG is not sufficient either, since the growth potentials for both, electricity trade and generation in eastern Europe reach their maximum in the scenario MITH.

In both of the 450 ppm CO_2-eq mitigation scenarios (MIT7 and MIT8), a similar trend can be observed as described above. In the case of

lower electricity demand (MIT7), southern Europe imports its sources from eastern Europe instead of western Europe, and only slightly decreases its general import dependency. In case of higher electricity demands, all regions install additional generation capacity with CCS, to cover growing demand.

Economic Implications

In the 450 ppm CO_2-eq scenarios it is found that the total discounted system cost in EU27+2 (excluding fuel cost for imported fossil fuels) are lower in case of no new investments in nuclear generation allowed (for run MIT7 -0.5% and MIT8 -1.5%), compared to the respective scenarios MIT1 and MIT2, where nuclear investments are available. This is due to the fact that less capital intensive technologies are installed in Europe in the scenarios MIT7 and MIT8. However, additional fuel costs for fossil fuels change this picture and raise the cumulative TDSC in the scenarios MIT7 and MIT8 above levels of the scenarios MIT1 and MIT2 (see table 6.3). Therefore, the results are highly sensitive to the assumptions on fuel prices. Additionally, the model results indicate that for the periods after 2050, the absence of nuclear generation would increase total system cost even further above the levels achieved in the scenarios where nuclear technology is available (run MIT1 and MIT2). Since further emission reductions are needed beyond 2050, the installation of CCS generation capacity would force late and more costly investments to achieve mitigation targets because CCS technologies still contribute to CO_2 emissions. This interesting result leads back on the issue of lock-in effects, which are described in section 2.3.3.

In line with this argumentation are the results of the 400 ppm CO_2-eq scenario. In both cases (MITG and MITH), higher cumulative total discounted system costs are expected from 2035 on, given that the more stringent climate target is still achievable. The results further indicate that in the scenarios which exclude nuclear generation (MITG and MITH), the total system costs are lower as compared to the reference scenarios until 2035.

TABLE 6.3.: *Comparison of cumulative investment costs (C. I.) and total cumulative discounted system costs (TDSC) in the year 2050, for selected technologies and different mitigation scenarios. The total discounted system costs for the scenarios MITA, MITB, MITG and MITH further include investment costs and fixed and variable operation and maintenance cost for transport specific demand technologies (cars). Therefore, these TDSC are only comparable in relative terms to the other given total system costs in the scenarios MIT1, MIT2, MIT7 and MIT8 where such cost estimates are not available.*

	C. I. Wind [Billion $] 2050	C. I. Nuclear [Billion $] 2050	C. I. Fossil [Billion $] 2050	C. I. Total [Billion $] 2050	Cum. TDSC [Billion $] 2050
MIT1	492	215	169	1494	9747
MIT2	575	378	223	1815	10055
MIT7	535	0	335	1516	9761
MIT8	652	0	496	1838	10109
MITA	481	315	127	1562	10135
MITB	634	528	223	2064	10613
MITG	543	0	367	1615	10186
MITH	701	0	562	2158	10710

Regarding cumulative investments, it is found that with increasing electricity demand, additional investments are needed. Due to the exclusion of investments in nuclear generation (runs MIT8 and MITH), a shift of investments towards CCS-technologies is found as described above. In both scenarios with high electricity demand, the investment cost are between 20% and 30% higher as compared to the scenarios with lower electricity demand (run MIT8 vs. MIT7, and MITH vs. MITG).

6.5. Restriction of Carbon Capture and Sequestration

6.5.1. Inputs and Assumptions

It has been shown that in case of restricted use of nuclear electricity generation a shift to power generation based on fossil fuels with carbon capture and sequestration is expected. However, today this technology faces partly similar constraints as nuclear generation (e.g. concerns about permanent storage of emissions/waste) as well as unresolved technical questions (e.q. upscaling, efficiency losses) since this technology is not yet available on a large scale. So far, only test plants with small carbon capture units have been deployed for coal based power plants. In this respect it is doubtful, if carbon capture is available in 2020, and if policy makers and the public supports this option for low CO_2-emission electricity generation in the future. However, in the energy field this technology is also seen as a potentially valuable option for electricity generation (Odenberger et al., 2008). As shown, this technology is important for achieving stringent mitigation targets when nuclear is not available. To evaluate boundaries and implications in case CCS is not available, a set of additional constraints is implemented in EuroMM. In the results presented so far, the option of carbon capture and sequestration only plays a major role in case nuclear power is excluded for electricity generation in the future. Therefore the already presented runs MIT7 and MIT8 as well as MITG and MITH were further extended by excluding CCS-technologies for power generation, and named as runs MIT9, MIT0, MITJ and MITK. By following this set of constraints, an almost complete renewable power generation sector is in focus and it is the aim of this set of scenarios to pinpoint possible technical and policy implications.

6.5.2. Results

Electricity Generation

In the analysis of the runs introduced here (MIT9, MIT0, MITJ and MITK) natural gas based electricity generation (without CCS), and renewable technologies are the sources for power generation, with low emission

levels (see table 6.4). In case of the 450 ppm CO_2-eq scenarios (MIT9 and MIT0), natural gas based power generation contributes to total generation between 21% and 27%, while in the case of more stringent climate targets (runs MITJ and MITK) this share is reduced to less than 6% (see table 6.4). According to the more stringent climate targets, solar PV and solar thermal, as well as biomass based electricity generation increase the output of electricity further, compared to the runs for the 450 ppm CO_2-eq target, while replacing electricity generation based on natural gas. However, the large increase in biomass power generation in the MITK scenario where electricity demand is high, is only possible, if biomass in large quantities can be imported from regions outside EU27+2. In the case of higher electricity demand and a 400 ppm CO_2-eq target, an additional 2.2 EJ of biomass need to be imported compared to MITA until 2050. Since it is unclear if this amount of biomass is available for Europe in the future, this issue needs to be further analyzed in a global model which accounts for global biomass potentials and regional allocations. However, the biomass imports are not distributed evenly between regions. While eastern Europe and northern Europe rely almost by 100% on own resources, southern Europe and western Europe are the main importers for additional biomass.

As mentioned above, additional solar thermal capacity (more than 220 GW installed in 2050 in MIT9 and MIT0) and solar PV capacity (more than 260 GW installed in 2050 for the runs MIT9 and MIT0) is built, with strongest growth in the years from 2040 on. While solar thermal systems are only expected to be built in southern Europe, solar PV capacity is expected to grow in most of the European regions, except eastern Europe. This is due to the fact that for eastern Europe the potential for solar electricity generation is expected to be small in the near future, while this regions still relies on fossil sources. Starting from a relatively low base of solar capacity, other options such as biomass based electricity generation are a more competitive option, to switch from fossil sources to CO_2-free generation in due time. Additionally, the potential for biomass based generation is higher in eastern Europe (without additional biomass imports from the rest of the world), and therefore more competitive, compared to solar generation.

TABLE 6.4.: *Electricity generation for the given energy carriers and the scenarios described in this section 6.5 and as defined in table 6.1. The electricity output is given for the four aggregated regions North, South, East and West.*

West	Hydro [TWh]		Natural Gas [TWh]		Biomass [TWh]		Oth. RET [TWh]		Wind [TWh]	
	2005	2050	2005	2050	2005	2050	2005	2050	2005	2050
MIT1	147	176	452	21	56	98	1	61	38	390
MIT2		177		38		102		61		482
MIT9		179		655		171		78		399
MIT0		179		744		486		116		571
MITA		176		8		85		61		388
MITB		177		6		122		61		544
MITJ		179		134		227		380		363
MITK		179		129		633		564		592
East										
MIT1	17	27	43	20	5	52	0	2	0	73
MIT2		27		21		59		2		73
MIT9		27		6		141		13		72
MIT0		27		0		284		12		80
MITA		27		0		56		2		65
MITB		27		0		69		2		78
MITJ		27		0		90		72		78
MITK		27		0		276		22		81
South										
MIT1	103	157	276	10	14	62	6	21	26	128
MIT2		157		17		65		29		143
MIT9		157		69		129		111		156
MIT0		157		14		289		115		193
MITA		157		5		70		19		119
MITB		157		17		73		36		152
MITJ		157		3		87		339		177
MITK		157		1		330		319		203
North										
MIT1	213	224	32	12	24	31	0	4	10	59
MIT2		229		26		31		4		95
MIT9		236		19		69		5		68
MIT0		255		45		94		5		94
MITA		224		4		24		4		70
MITB		232		13		25		4		103
MITJ		226		4		70		3		74
MITK		246		18		112		8		98

Backup capacity which is needed in these scenarios due to the high share of intermittent sources (e.g. solar and wind power) is based on thermal capacity using natural gas and biomass as input fuels, as well as from hydro power capacity and grid interlinkages with neighboring regions.

Electricity Trade

Electricity trade patterns in the scenarios MIT9, MIT0, MITJ and MITK are mainly determined by the availability and use of renewable energy for power production. Since eastern Europe needs to shift from fossil generation to CO_2-free electricity generation, this region reduces its electricity exports to very low numbers, compared to scenarios, where fossil generation is still available (e.g. MIT1, MIT2 among others). Due to this reduction in available trade capacity from eastern Europe, other regions need to increase own electricity production. In the scenarios MITJ and MITK, southern Europe increases the output of solar based electricity production, especially in the last periods of the model horizon, and becomes independent of electricity imports. Western Europe on the contrary needs to import electricity in the scenarios of stringent climate targets, since electricity demands can not be fully covered by CO_2-free electricity. One of the major exporting regions for covering electricity demand in western Europe is therefore northern Europe (e.g. Scandinavia), which increases electricity exports to Germany. Additional electricity for exports is based on wind and biomass.

Under less stringent climate targets (e.g. 450 ppm CO_2-eq), the available potentials of renewable sources have smaller impacts on electricity generation for the different regions. Since natural gas based electricity generation plays a larger role, especially in western Europe, trade flows look slightly different in the runs MIT9 and MIT0. Western Europe exports electricity to southern Europe, which is more cost effective than producing solar based electricity generation in southern Europe. However, eastern Europe reduces electricity exports since the competitiveness of the available generation capacity is low, compared to the scenarios where

coal based electricity generation is favored. No changes compared to the 400 ppm CO_2-eq scenarios are found for northern Europe, which exports CO_2-free electricity to western Europe.

Economic Implications

The exclusion of large scale electricity generation technologies with low or zero CO_2 emissions in the 450 ppm CO_2-eq scenario shows similar results, as compared to the results excluding new nuclear power. The total discounted system cost in the run MIT9 are only 0.5% higher compared to the costs derived in scenario MIT1 until 2050 (see table 6.5). This implies that an electricity system based on renewable power and natural gas based electricity generation is cost competitive compared to a system in which coal and nuclear power play a major role for electricity generation until 2050. Again, the investment in capital intensive technologies such as coal and nuclear based capacity with higher operation cost together with lower fuel cost (for coal and nuclear energy compared to natural gas and biomass) is as costly as a system with less capital intensive capacity installation, accompanied by more expensive fuels (see also C.1 for the comparison of technology costs). For the same scenario comparison (MIT1 vs. MIT9), the cumulative investment cost are approximately 5% higher in the scenario MIT9, due to the higher investment in wind and solar capacity, as well as biomass based generation technologies.

In the runs MIT0, MITJ and MITK, the discounted system cost as well as the investment cost are slightly higher as compared to the corresponding scenarios MIT2, MITA and MITB (in the range of less than 2% for the total discounted system cost in all scenario comparisons, see table 6.5). In general terms, it is found that the tighter the boundaries are for the system (e.g. higher climate targets as well as higher demands) the more costly the system is. However, the total cost increase is estimated to approximately 2% for the scenario MITK, compared to the scenario MITB, although the cumulative investment cost are approximately 40% higher for the same comparison. Due to the fuel savings and differences in the cost of operation and maintenance for the different technologies, the difference in the total system cost is small. The difference in electricity

TABLE 6.5.: *Comparison of cumulative investment costs (C.I.) for selected technologies and scenarios, together with the according cumulative total discounted system cost (Cum. TDSC). "C. I. Total" includes investments in hydro power capacity, nuclear capacity, other renewable generation capacity as well as fuel production and district heat generation capacity.*

	C. I. Wind [Billion $] 2050	C. I. Fossil [Billion $] 2050	C. I. Solar [Billion $] 2050	C. I. Total [Billion $] 2050	Cum. TDSC [Billion $] 2050
MIT1	492	169	8	1494	9747
MIT2	575	223	9	1815	10055
MIT9	554	163	143	1561	9800
MIT0	681	176	194	1919	10144
MITA	481	127	8	1562	10167
MITB	634	223	16	2064	10613
MITJ	567	152	835	2288	10442
MITK	715	177	1001	2857	11019

demand (run MIT0 versus MIT9 and MITK versus MITJ) increases the total discounted system cost by additional 4-5%. This cost increase is therefore higher as compared to cost increases due to technological or policy constraints.

6.6. Summary of Results

Based on the scenario analysis described in this chapter, it is found that stringent climate targets and the corresponding greenhouse gas emission reductions can be achieved under various political and technological constraints. In a first set, the importance of energy efficiency gains, especially in case of reducing electricity demand from the residential and services sector, is analyzed. It is found that such efficiency gains are important but not mandatory to achieve climate mitigation targets. Although efficiency measures are not directly incorporated in this analysis, the results indicate that efficiency measures can substantially contribute

to reducing investments in the electricity generation sector. Additionally, the costly imports of fossil sources such as coal, oil and natural gas can be reduced.

In a second set of model runs, the impact of different technological constraints regarding the contribution of wind power to total electricity output is analyzed. It is found that up to 1100 TWh of electricity could potentially be generated annually in Europe by 2050, contributing by up to 35% of total generation accross Europe. These findings are approximately 50% above the output of wind power in those scenarios, where wind power is limited to 30% of total generation in each region. Therefore it can be shown that wind power is a competitive alternative for CO_2-free electricity generation which is needed to reduce CO_2 emissions in a cost optimization environment.

The last scenario runs in this model analysis investigate the impact of uncertainty in the availability of large scale technologies such as nuclear power and fossil generation with CCS. In this analysis it is found that such technologies are not mandatory in the future, to achieve stringent climate targets. Other CO_2-free electricity systems such as solar generation as well as biomass based generation are available, to cover final energy demand. However, the exclusion of such technologies increases total system cost, as well as relevant imports of biomass for electricity generation.

6.7. Discussion and Conclusion

As already mentioned in section 5.7, a high share of wind power in total generation is only likely, if some technological barriers can be removed in the future. As described earlier, the intermittent characteristic of wind power is one of the major problems which needs to be considered, for long term integration of expanded wind generation in the grid. However, there are several factors and solutions which already today allow for large integration of wind power in electricity grids. For instance, by integrating wind capacity located in different regions, the risk of no wind power being

available at any time is reduced (geographic diversification). By additional investments in backup capacity, the risk of blackouts is further decreased. Nowadays, gas fired power plants are often used as backup capacity due to their short start-up time. In EuroMM, the results do not show specific investments in one technology as backup capacity - rather different systems such as biomass-based power plants or hydro power plants are used as backup capacity.

One further important aspect of high shares of intermittent sources is the bilateral trade of electricity within Europe. Open access to the electricity grid and the trade of electricity from renewable sources to regions with low access to CO_2-free technologies is desirable to include high shares of wind power into the market. However, additional investments in high efficient electricity grids, including high voltage direct current grid lines, is necessary to connect centers with high output of wind power (e.g. UK and Spain) with demand regions with low availability of renewable sources (e.g. Italy).

To further analyze the reliability of such systems with high penetration of intermittent sources such as wind power, dispatch models are necessary to investigate shorter term time steps than presented in EuroMM. Additionally, it is expected that the development of storage capacity connected with wind power systems (e.g. pressure tanks / flywheels also in connection with diesel generators) as well as pumped hydro power will contribute to the avoidance of blackouts.

In cases where CO_2-free power generation technologies (such as nuclear and CCS) are limited due to political reasons as described in sections 6.4 and 6.5, stringent climate targets are still achievable, although to a slightly higher cost. The results of section 6.4 show that the limitation of nuclear power shifts electricity generation towards fossil technologies equipped with CCS, to comply with climate targets in this cost optimization analysis. Additionally, by limiting the use of fossil technologies with CCS, the deployment of renewable technologies expands. However, such a system relies on the availability of biomass from other world regions, and it remains an open question, whether the world potential for biomass is large enough, to provide sufficient renewable energy. The importance of biomass imports could be reduced by increasing the share of wind

power in the system.

   As found in the analysis of different policy and technical constraints presented in this chapter, trade-offs exist between different options of achieving stringent climate mitigation targets. One option to comply with high emission reductions is to increase energy efficiency in the final energy demand sectors. By doing so, less investments are needed for CO_2-free electricity generation, and less fossil fuel imports are required. However, costs for efficiency measures, such as better insulation of housing, and the use of high efficient appliances reduce the cost advantage of such system. If final energy demand can not be reduced significantly, high cost for additional CO_2-free electricity generation capacity is needed. Therefore, additional investments in larges scale technologies, such as nuclear power and fossil technologies with CCS are needed, although such investment projects often face problems of public acceptance. However, it is noteworthy that even with high efficiency gains, the investment in large scale technologies is cost effective, since old generation capacity needs to be replaced in the future. In general, it can be said that by excluding one or more technical options to reduce greenhouse gas emissions, the total system cost will increase, compared to a system where all options are available.

Therefore, different policy support measures are necessary to overcome barriers in the development of a more sustainable energy system in Europe. On the demand side, regulations and support measures on housing standards and insulation, as well as the use of efficient appliances reduce the demand for heating and electricity. The support for renewable energies, such as feed-in tariffs, funding of research and development, can reduce the need for large scale technologies in the future. Additionally, the removal of barriers regarding grid integration of large amounts of intermittent sources is crucial. Therefore, additional support is needed to modernize grid infrastructure, to improve dispatch management and to extend storage capacity, to provide sufficient grid stability. Although not especially discussed in the course of this dissertation, support for renewable energies is of high value. For further insights about such measures the reader is referred to Reiter et al. (submitted), which presents results of an energy system which is partly driven by financial support for

renewable technologies. However, by either subsidizing renewable technologies or introducing targets for specific renewable energy technologies (RET), other factors than specific costs of technologies become more important for finding relevant solutions for the energy system under climate targets.

Further policy support measures are likely to be needed for large scale technologies regarding safety issues of nuclear power plants, as well as regarding disposal concerns of nuclear wastes and longterm CO_2 storage.

7. Summary and Conclusions

The objective of this dissertation was to analyze possible development pathways of the European energy conversion sector under a set of climate constraints, as well as to analyze uncertainties of the main assumptions driving the development of the energy system. Two major scenarios of climate development exist for the future, which influence policy decisions and investment strategies of utilities. This thesis has aimed at analyzing the interlinkages between climate constraints and possible adaptation and mitigation options by focusing on three key issues:

- The impacts of climate change on the European energy conversion sector and the related costs and technology pathways for adapting the energy infrastructure to a changing environment

- The impacts of stringent climate mitigation targets for limiting temperature increase to below 2 °C, relative to pre-industrial levels, on European energy system costs and the according capacity installations of power generation

- The role of different policy and technological uncertainties on achieving stringent climate targets and the related costs

In the next sections, a summary regarding the key questions, and a short review of the steps undertaken to achieve the results presented in this dissertation, is given. The chapter closes with the final conclusions and an outlook of potential improvements and future work.

7.1. Summary

7.1.1. Model and Scenario Development

At the time these lines are being written, policy and decision makers are discussing at the UNFCCC COP-15 meeting in Copenhagen, Denmark, the international follow-up agreement to the Kyoto Protocol (Kyoto Protocol, 1998), to achieve greenhouse gas emission reductions in the future. The investigation of different scenarios, which are in the range of possible outcomes of the COP-15 meeting regarding greenhouse gas emissions and likely reduction targets, is helpful to provide insights into impacts and necessary changes, arising from decisions taken, in the context of the UNFCCC work.

To answer the research questions given above, which embed possible future scenarios, a comprehensive analysis tool has been built to investigate the development of the European energy conversion sector under specified assumptions for the future. The focus of the present work is put on the energy conversion sector, as one of the main contributors to anthropogenic greenhouse gas emissions.

The model tool (EuroMM) developed in the course of this dissertation represents the European energy conversion sector including the whole energy chain, from primary energy sources to power generation and fuel production, and further to final energy demand sectors. This model was newly built and includes as main features the level of details for electricity generation technologies, the implementation of the electricity grid, and a seasonal description of energy conversion and demand. The level of detail in the electricity generation portfolio is of importance, to give the model the flexibility to chose between technologies with different advantages and disadvantages regarding cost, efficiencies and availabilities to cover final energy demand. The integration of the electricity grid is of importance, to depict possible impacts of the use of different European energy sources (e.g. fossil sources and renewable sources), on electricity trade between European countries. This level of detail in the model ensures that relevant insights can be gained, in context of the research

questions. The availability of seasonal parameters in the model is an additional advantage, to assess seasonal impacts of climate change on the energy conversion sector. A broader overview of model features and a more detailed description of the model can be found in chapter 3.

The model tool was used to develop and investigate different scenarios of the future energy conversion sector in Europe, to find answers to some of the various challenges which are expected in the future. An overview of such future challenges is given in chapter 2. These challenges comprise impacts on all levels of the energy chain. However, only selected scenarios regarding climate change adaptation and mitigation as well as uncertainties within these scenarios were analyzed in more detail. Other challenges for the energy sector, such as depleting fossil resources in some European countries and the security of energy supply, were not considered in this dissertation. Therefore, three major story lines were selected and analyzed in more detail, to describe impacts and changes needed to the energy system, to cope with such challenges (see chapters 4, 5 and 6). These story lines and related findings are summarized in the following sections.

7.1.2. Climate Change Adaptation

In a first analysis, the model was used to investigate possible impacts of climate change on the energy conversion sector in Europe. Therefore, the energy system was analyzed under the assumption that ambient temperatures rise by 4 °C until 2100, compared to pre-industrial times. According to the findings in the fourth assessment report of the IPCC (Bernstein et al., 2007), this temperature increase is a likely development in the future, if greenhouse gas concentrations rise unmitigated.

Mainly two effects drive the changes in the energy system in terms of electricity generation, which are rising temperatures of rivers used for cooling purposes, as well as changes in the flow pattern of rivers in Europe. Rising river temperatures are of relevance, since river temperatures can be expected to be above environmental regulatory threshold values and therefore, additional investments would be needed for cooling ther-

mal power plants. Different advanced cooling technologies are available today, such as dry cooling, wet cooling and hybrid systems, to provide sufficient cooling for power plants also in the future. In this analysis it has been shown that extensive installations of such advanced cooling technologies, as well as structural changes are needed in the coming decades, to adapt the energy infrastructure to climate change. For instance, it is expected that southern Europe will need to equip almost all of the thermal electricity generation capacity until 2050 with advanced cooling facilities, to avoid electricity shortages during summer months, from 2020 onwards. Additionally, southern Europe is likely to import more electricity from central Europe which is less affected by climate change. However, further site specific analysis is needed to investigate which specific cooling technology is suitable for providing cooling at lowest cost.

Additionally, throughout Europe, changes in the flow patterns of rivers influence power production from hydro power plants, with positive (northern Europe) and negative (southern Europe) impacts expected. In northern Europe it is likely that the annual potential for hydro power will increase due to more rainfall during the year, while the seasonal changes of precipitation (snow/rain) is likely to influence seasonal output. However, to profit from increasing potentials, additional hydro capacity is needed, which is not fully reflected in this analysis. In southern Europe, reduced flow is likely to limit the output of hydro power, as well as further reduce available cooling capacity for thermal electricity generation. However, by switching to dry cooling systems, positive feedback can be achieved outside the energy conversion sector, since water demand is reduced, freeing resources for other demand purposes, such as drinking water or agricultural services (e.g. irrigation). In this model analysis it is found that up to 500 million m^3 of water can be saved per year until 2050, if advanced cooling facilities are installed.

Further impacts on the energy system are expected from an increase of extreme events (e.g. heavy storms and floods), which are posing threats to the energy infrastructure. However, reliable data for such events and especially return periods are scarce, and related impacts such as uprooting of infrastructure and building of additional dams, were not considered.

7.1.3. Climate Change Mitigation

Climate science is indicating that with rising greenhouse gas emissions, the global average temperature is likely to rise and therefore, the earth's climate system is influenced. To avoid such an occurrence, stringent greenhouse gas reductions are needed in the future, to stabilize atmospheric greenhouse gas concentrations. A high share of anthropogenic greenhouse gas emissions is based on the use of fossil fuels in all sectors along the energy chain. To comply with emission reduction targets, a shift towards more sustainable energy systems is needed in all regions of the world. Looking at Europe, the model results indicate that an energy conversion sector with very low greenhouse gas emissions is achievable until 2050. In the analysis of the 400ppm CO_2-eq scenario it is found that up to 90% of greenhouse gas emissions can be removed from the energy conversion sector. However, to achieve such energy system, investments in various renewable technologies, such as wind power, biomass based electricity generation, geothermal and ocean based electricity and solar electricity, as well as other CO_2-free technologies, such as nuclear power are needed. It is found that especially wind power as a CO_2-free electricity generation system is cost competitive in the future, compared to other conventional generation systems. However, the intermittent characteristic of wind power raises questions about the extent, to which wind power can be integrated in the electricity network. To address such issue, the maximum contribution of wind power to total production was limited to 30% in all regions.

One important driving parameter for the scenario analysis is the efficiency and possible efficiency gains in the final energy demand sectors. If the efficiency of appliances in the final energy demand sectors can be substantially improved in the future, the need for costly investments in CO_2-free electricity generation capacity could be reduced, and therefore climate change mitigation targets are more likely to be achieved. However, as the model results indicate, such efficiency gains are not mandatory to achieve even very high emission reduction targets, but lower the electricity system cost substantially.

Due to the uneven distribution of renewable sources across Europe, it is found that further investments and capacity building of transmission lines is necessary to lower electricity system costs in the future. CO_2-free electricity is produced in regions with high renewable potentials, and excess electricity is traded to regions with low access to renewable sources, to achieve stringent climate targets. For many regions in Europe, the electricity trade pattern changes under climate mitigation efforts and regions which are electricity exporters today are likely to become dependent on electricity imports from CO_2-free sources.

In addition to the above mentioned changes in the electricity sector of Europe, further emission reductions are needed outside the power generation sector, to reduce greenhouse gas emissions to levels which allow stabilizing climate change at below 2 °C temperature increase until 2100. First model results with stable greenhouse gas emissions outside the electricity sector had been proven infeasible, to achieve stringent reduction targets. Therefore, especially the transportation sector with a high dependency on fossil sources for energy purposes needs to reduce the overall output of greenhouse gases. However, other sectors such as the services sector and the industrial sector need to reduce greenhouse gas emissions as well.

7.1.4. Constraint and Uncertainty Analysis

Given the specific characteristics of scenario analyses, the necessary assumptions are underlying uncertainties, which need to be addressed. The level of uncertainty for the different model input parameters varies, regarding impact on model results. Therefore, the driving parameters for the model results of the mitigation scenarios were analyzed to provide insights in the robustness of the findings. Uncertainties exist regarding levels of efficiency gains in the final energy demand sectors, regarding availability of CO_2-free electricity generation technologies as well as the limits of integrating large shares of intermittent sources into the electricity grid. All of these parameters have been analyzed, regarding their impacts on overall results for achieving stringent emission reduction targets (see chapter 6). It is found that all parameters influence the results in terms of

expected overall system cost although to different degrees but more importantly, different assumptions for these parameters do not prevent from achieving stringent emission reduction targets in this model analysis.

As a main driver for cost increases in the energy systems, the level of energy demand is identified. If the total electricity demand in 2050 is 50% higher, as compared to the assumptions used in the underlying mitigation scenarios, the total discounted system cost increase by up to 6%. However, higher investment cost for generation technologies, such as solar or ocean based systems are partly compensated due to the avoidance of fuel costs which are needed for conventional electricity generation systems.

Given the possibilities of modeling intermittent sources in this cost optimization framework it is shown that wind power has a large potential for contributing to CO_2-free electricity generation. Under the given set of assumptions it is found that up to 35% of total generation in Europe can be based on wind power until 2050. This large share of wind power can be achieved if technological barriers can be overcome in the future, and if electricity trade accross borders can be extended from regions with a large potential for such sources to regions with low wind availability for power production.

Additionally, it is found that under specific conditions, large scale electricity generation systems such as nuclear power and fossil generation equipped with CCS are not mandatory to achieve stringent climate mitigation targets in Europe. Additional investments in other CO_2-free technologies, such as solar electricity generation capacity and biomass based electricity generation is needed to cover final energy demands. The necessary biomass based electricity generation is only available, if large amounts of biomass can be imported from regions outside of Europe.

7.2. Conclusions

7.2.1. Climate Change Adaptation

It is one of the first times that the impact of climate change on the energy conversion system of Europe has been analyzed in a quantitative way, regarding cost and electricity output of various generation systems. As can be seen from the analysis presented in this dissertation, even in the absence of efforts to reduce greenhouse gas emissions, significant technical change would be needed in the European electricity sector, to adapt to the impacts of climate change. In particular, climate change will pose major adaptation challenges in southern Europe. In absence of mitigation efforts, utilities and regulatory authorities should consider the planning of appropriate investment and policy measures, to guarantee secure power generation under climate change.

In this analysis, a potential future conflict between environmental regulations and the security of electricity supply has been identified. Specifically, it has been noted that climate change is likely to increase river temperatures in many parts of Europe (particularly southern Europe) above regulatory thresholds, governing whether the water can be used for cooling thermal power plants. A strict application of these regulatory thresholds may force the partial or complete shutdown of some thermal power plants during summer months, which may threaten the electricity supply. Thus, authorities may be tempted to temporarily suspend these environmental regulations. However, this allowance comes with the cost of damages to the ecological system. By analyzing future conditions of water runoff and temperature, utilities will be able to identify where there will be a need for investment, to satisfy the environmental regulations.

Additionally, the management of hydro power resources will need further investigation to cope with changes in the potential for hydro power production. While southern regions are likely to face reduced rive runoff, additional investments for e.g. increasing reservoirs might be necessary to avoid reductions in hydro power generation. Nordic countries are likely to profit from increasing hydro power potentials, if changes in river runoff

can be used by increasing the reservoir capacity or additional installation of generation capacity.

Under the assumption that hot weather extremes will occur more frequently due to climate change, central European countries are expected to face shortages of their electricity production in summer, similar to the impact observed in the hot summer of 2003. Accordingly, additional investments will be necessary in these regions, to ensure sufficient reserve capacity is available to guarantee stable grid operation. Additionally, it is noted that today nuclear power plants generally undergo refueling and maintenance during summer months, and are not available for power production. With growing electricity demand, combined with reduced generation efficiency and availability, it is likely that more of these plants will need to remain on-line during summer, to prevent from possible shortages. This will require changes to the planning of scheduled downtime well in advance, and additional reserve capacity.

7.2.2. Climate Change Mitigation

A number of important changes are required in the energy conversion sector, to achieve stringent mitigation targets explored in this analysis. These include an almost complete phase-out of CO_2 emitting fossil generation in Europe, the large-scale deployment of renewables, and high efficiency gains in the various energy demand sectors.

Realizing these different sectoral improvements at high level is likely to necessitate substantial government support, over a long period. This support will most likely need to combine broad climate policies with long-term targeted sector-specific measures. In general, the phase-out of CO_2 emitting fossil generation will be brought forward by high and stable CO_2 prices, which are likely to be achieved by CO_2 taxes or cap and trade systems.

Additionally, an open market for electricity trade substantially lowers the need for costly technological mitigation options. By supporting the electricity trade from regions with a high potential of renewable sources

to regions with low availability of such resources will be beneficial in terms of cost for mitigating climate change. However, two constraints possibly limit the policy support which is needed to allow for the expansions of the electricity grid for trade purposes. By increasing electricity imports, countries rely more on their neighbors and therefore might be concerned about too high levels of import dependency. Additionally, projects for the expansion of the grid infrastructure are often under pressure from various opponents and therefore, policy support is needed to allow for timely linking new electricity generation sites with high electricity demand centers.

7.2.3. Uncertainty Analysis

In this dissertation it is found that energy efficiency improvements and related energy demand reductions are favorable in terms of cost of the energy conversion sector, to achieve stringent climate mitigation targets in the future. However, historic trends show a close relation between GDP-growth and energy demand increases and this trend is likely to be continued in the future. Due to the expected increase of GDP in the future also energy demand is likely to increase further. Therefore, various steps to improve energy efficiency in the final energy demand sectors such as implementing higher building standards and standards for appliances would be needed to decrease future energy demand. It is open, if such more technical measures are sufficient to achieve relevant demand reductions, and therefore, the question of how the relation between GDP-growth and energy demand increase can be resolved in the future remains unanswered.

Independent of the level of final energy demand, additional efforts are needed to integrate large amounts of intermittent sources into the electricity grid, to ensure stable operation conditions and to provide sufficient electricity to cover final energy demand based on CO_2-free generation technologies. Although it is expected that technical constraints can be overcome in the future to integrate higher shares of intermittent sources, further research is needed to prove the system stability under such conditions. This includes research in the area of electricity storage which links between intermittent electricity generation and final energy demand.

Resolving open issues regarding intermittent sources is additionally important, if other CO_2-free large scale technologies such as nuclear power and fossil generation with CCS is not available in the future, due to technical or political reasons. The results indicate that such technologies are not mandatory to achieve stringent climate mitigation targets, but other issues such as intermittent sources and grid stability need to be considered. Additionally, the question of biomass imports for electricity generation need to be analyzed further, especially in the context of other competitors to Europe for such sources.

7.2.4. Integrating Adaptation and Mitigation in European Policies

In this dissertation, scenarios where analyzed, which treat adaptation and mitigation separately for the energy conversion sector in Europe. However, it is almost certain that a future will be seen, where elements of both adaptation and mitigation are required, and policy makers will need to combine local adaptation measures with EU-wide adaptation and mitigation regulations. In this dissertation, the possible impacts of climate change on the energy conversion sector were shown for a first time, including the technology options and costs for adapting to these impacts. However, it is important to recognize that the extent of the required adaptation is dependent on the effectiveness of mitigation policy – more effective mitigation policies will reduce the need for further adaptive measures. Since not all European regions are affected in the same way from climate change, policy makers will also have to deal with defining an equitable sharing of the burden of financing adaptation and reducing emissions of greenhouse gases.

To minimize the impacts of climate change on the energy conversion system, policies which are supporting climate change mitigation measures must be continued. In this case, an adequate regulatory framework is needed at sectoral and national levels, in order to support the development of a broad basket of low-carbon technologies and efficient appliances.

In the cost optimization framework of this analysis, a set of CO_2-free technologies contributes to achieving climate mitigation targets. It is found that especially wind power is a competitive generation technology and is also contributing to electricity generation under the adaptation scenario. Therefore, the continuation of favorable conditions for wind power is needed to exploit this resource to a maximum extent.

Independent of the future scenario which is applied in the model analysis, the future electricity system is highly depending on the existing infrastructure. Due to the long lifetime of generation capacity, a complete turnover of all power plants in Europe will take several decades. Therefore, investments decisions taken today are likely to influence the generation portfolio past 2050, which is beyond the model horizon applied in this analysis. To attract investment in electricity generation capacity and grid infrastructure irrespective of the scenario, policy support is needed to guarantee stable conditions, investors can base their decisions on. As long as political framework conditions are undefined regarding long term climate policies and policy support for specific generation technologies, infrastructure investments in large amounts are more difficult to mobilize. In this respect it is also noteworthy that although the renewable electricity generation technologies are more costly in terms of capacity investment, high cost savings can be achieved since spendings on fossil resources are reduced.

7.3. Potential Improvements and Future Work

In general, one should take into account that there are a number of uncertainties and limitations to the analysis presented here. Firstly, there is limited knowledge on likely changes from climate change on the environment such as river flow patterns or extreme events, which is important for estimating impacts on the energy conversion infrastructure. To analyze the impacts on the energy conversion sector in more depth, some further research would be needed to improve the quality and quantity of data, concerning the impacts of climate change on large scale. This includes

reliable data about the change in weather conditions, especially extreme events and their return periods, since these extreme events are likely to drive costs for reinforcement and upgrading of infrastructure. Furthermore, investigations about likely changes of wind speed due to climate change help to estimate changes in wind power potentials across Europe. This is especially essential, since wind power is one of the most cost competitive CO_2-free electricity generation technologies in the future. Depending on the changes in average wind speed as well as peak wind speed, negative as well as positive feedbacks are possible.

Additionally, the planning of expected downtimes for refueling nuclear power plants could be considered under climate change scenarios. This is of interest since such scheduled downtimes are likely to coincide with higher electricity demand in summer periods, due to increasing electricity demand for space cooling.

However, the main difficulty in obtaining reasonable estimates on infrastructure changes and associated costs in this analysis is translating site-specific information about environmental parameters (e.g. river runoff and temperature) into aggregate model assumptions, which describe future developments of countries and groups of countries. In the literature, there are data available on local impacts of climate change on different sectors, regions and even communities, including factors, such as energy demand changes due to higher temperatures. However, on the large scale of countries and country associations, such as the European Union, the impacts on the energy conversion sector, especially electricity generation have hardly been investigated. These challenges were addressed in this thesis by investigating local impacts of climate change and estimating their influence on large scales, as well as by including available data on country level in the European model. It is expected that by using additional information from other sources (e.g. additional GIS-based data), the robustness of the analysis could be improved.

Regarding the climate mitigation scenarios, further work should be conducted to estimate the impact of high shares of intermittent sources on the stability of transporting electricity in the grid. Although this issue has been addressed in this dissertation, the time resolution in the model re-

mains low. By increasing the time resolution in scenarios for electricity supply and demand, better insights could be gained. Therefore, it might be necessary to use different modeling tools, such as dispatch models, to fully investigate the possible advantages and disadvantages of such systems with a high share of intermittent sources.

Additional mitigation scenarios could be analyzed, regarding security of supply and dependency from electricity trade. It has been shown in this dissertation that electricity trade patterns are likely to change in the future, where countries with a high availability of cost competitive renewable sources export excess electricity to regions, with low access to CO_2-free electricity capacity. If electricity imports are not available due to concerns regarding import dependency as well as other limitations of fully deploying the electricity grid, additional CO_2-free electricity generation capacity from other sources need to be available in those countries with low availability of relatively cheap renewable sources.

Model improvements within EuroMM should aim for better description of the different energy demand sectors. Due to the dependency of exogenous demand assumptions, the model is limited regarding projections of beneficial trade offs for emission reductions in the various demand sectors. By including those demand specific features in EuroMM, the range of scenario analyses can be further extended. The analyses of policies regarding energy efficiency improvements, and their influence on the power generation sector are of valuable interest.

Additionally, the resolution of the seasonal parameters should be increased to fully depict the influence of seasonal variability on electricity generation and demand.

Furthermore, two technological systems might be necessary to be included in further analyses. The development of electricity storage systems should be analyzed regarding economical prospects and impacts on grid stability for large shares of intermittent sources. Additionally, the linking of electricity generation, storage and demand via smart electricity grids should be considered. Both are promising technologies for future market entrance, with the potential to resolve certain issues of stable grid operation discussed earlier in this dissertation.

Future work could also include linking the multi-regional European MAR-KAL model EuroMM to the global model GMM (Gül, 2008), as well as the regional MARKAL model of Switzerland (SMM) (Schulz, 2007), which are both available in the Energy Economics Group at the Paul Scherrer Institute. By linking EuroMM to the global model GMM, e.g. specific questions such as the availability of biomass resources for Europe can be resolved under stringent climate mitigation scenarios. Additionally, results of the European model on growth potentials for specific technologies would be available for the global model.

On the other hand, the bilateral exchange of information between EuroMM and SMM allows to analyze the interlinkages between single regions and the surrounding regions regarding electricity trade, and likely implications of specific mitigation policies.

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Appendices

A. Boundary Conditions Baseline, EuroMM

The figure A.1 describes the interlinkages between different bottom-up models and top-down models and EuroMM. This model setup was designed for the ADAM-M1 work package, analyzing climate change mitigation options for the European energy conversion sector. For further details see Jochem et al. (2007).
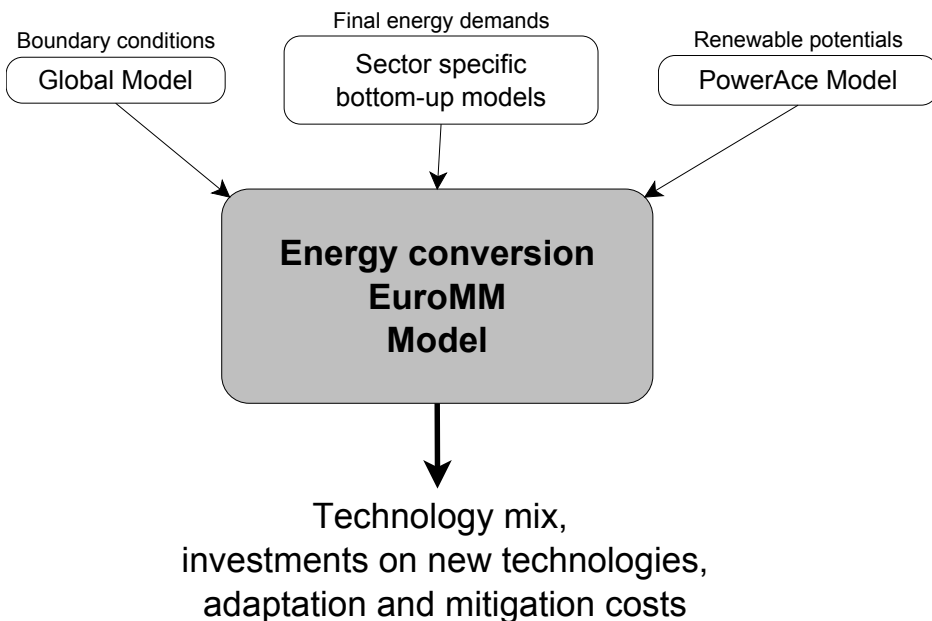
FIGURE A.1.: *Interlinkages between EuroMM and other models from ADAM-partners.*

B. Additional Input/Results Adaptation Scenario

B.1. Air Temperatures
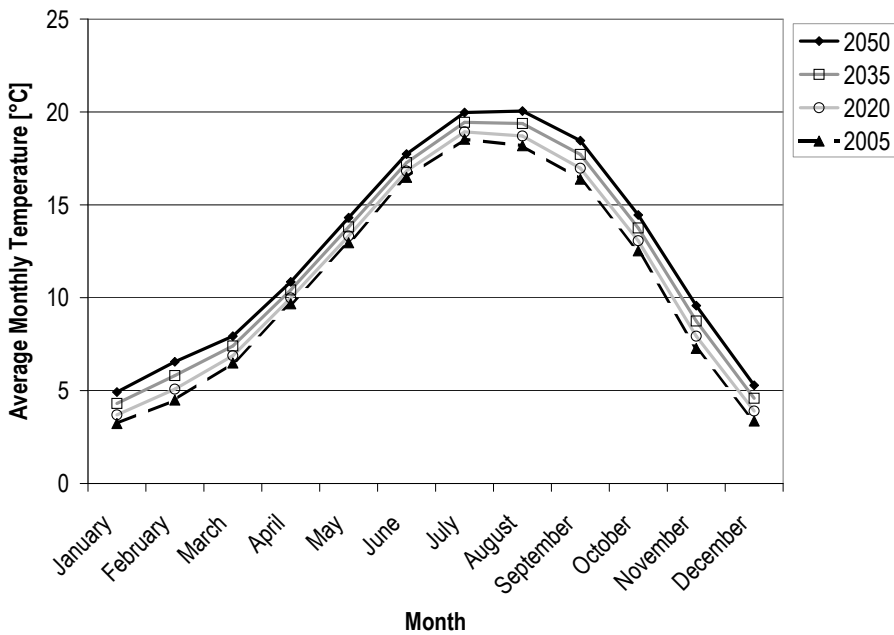
FIGURE B.1.: *Monthly average air temperature development for the selected region France under climate change. An average increase of plus 2° C is expected until 2050 compared to pre-industrial levels according to Isaac and van Vuuren (2009).*

B.2. Fuel Production

Up to 2020 the main fuel production of biofuels is based on the esterification of oil crops such as rape seed. From 2020 on, when advanced biofuel production technologies are expected to be available, a shift towards advanced biofuel production technologies is found. These technologies are based on cellulosic biomass and wood residues to produce biofuels.
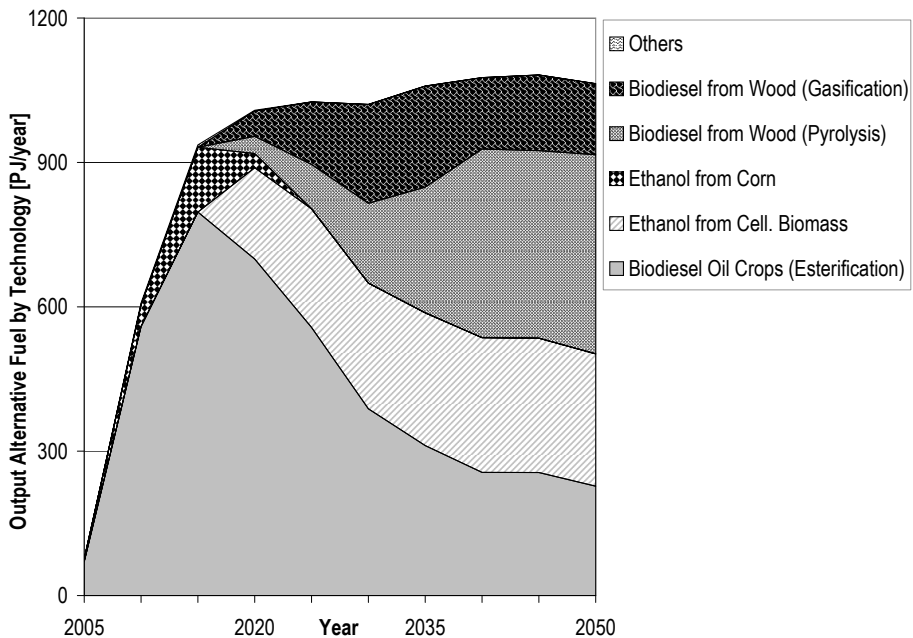
FIGURE B.2.: *Alternative fuel production in the adaptation scenario. The level of fuel demand is based on input assumptions derived from (Jochem et al., 2008), whereas the shares of the different biofuel production technologies are endogenous model results. More details about technology descriptions can be found in (Gül, 2008).*

C. Technology Specifications

C.1. Technology Specifications for Electricity Generation

C.2. Technology Specifications CCS

TABLE C.1.: *Cost and performance parameters of selected electricity and heat generation technologies. 1) indicates that regional and seasonal specific load factors are assumed rather than annual load factors. 2) indicates that capacity factors are used based on GIS data for different wind speed categories (see Reiter et al. (submitted) for further specifications).*

Technology	Start Year	Lifetime	Load Factor start	Load Factor 2050	Electric Efficiency start	Electric Efficiency 2050	Investment Cost start $/kW	Investment Cost 2050 $/kW	Fixed O&M Cost start $/kW/yr	Fixed O&M Cost 2050 $/kW/yr	Var. O&M Cost start $/GJ	Var. O&M Cost 2050 $/GJ
Electricity only												
Coal Conventional Thermal	2005	30	0.85	0.85	0.38	0.39	1241	1072	50	45	0.79	0.63
Pressurized Coal Supercritical	2005	30	0.85	0.85	0.44	0.50	1354	1016	45	41	0.79	0.63
Coal IGCC	2005	25	0.85	0.85	0.45	0.51	1693	1354	51	46	1.57	1.29
Lignite Conventional Thermal	2005	30	0.85	0.85	0.35	0.38	1241	1072	56	52	0.79	0.63
NGa Gas Turbine in Combined Cycle (GTCC)	2005	25	0.90	0.90	0.55	0.62	508	451	20	18	0.63	0.50
NGa-powered Turbine	2005	25	0.29	0.29	0.35	0.45	395	339	20	18	1.57	1.29
NGa Conventional Thermal	2005	30	0.85	0.85	0.40	0.42	1016	903	30	27	0.63	0.50
Oil Conventional Thermal	2005	30	0.90	0.90	0.39	0.41	959	846	30	27	0.63	0.50
Oil GTCC	2005	25	0.90	0.90	0.22	0.25	508	451	20	18	0.63	0.50
Pressurized coal supercr. with CCS	2005	30	0.85	0.85	0.35	0.42	2359	1467	53	47	0.95	0.78
Coal IGCC with CCS	2005	25	0.85	0.85	0.38	0.45	2229	1557	63	56	1.72	1.44
NGa GTCC with CCS	2005	25	0.90	0.90	0.48	0.57	925	677	25	22	0.78	0.66
Conventional Light-Water nuclear Reactor	2005	40	0.80	0.85	0.34	0.39	2201	1806	68	61	0.25	0.19
New Nuclear Design	2005	40	0.80	0.85	0.30	0.45	6771	1806	113	63	0.94	0.25
Conventional, large-size Hydroelectric	2005	45	1)	1)	1.00	1.00	2934	2257	45	41	0.09	0.06
Small-size Hydroelectric (<10 MWe)	2005	30	1)	1)	1.00	1.00	2370	2201	56	46	0.00	0.00
Solar PV with Network Connection	2005	25	0.17	0.19	1.00	1.00	6771	1693	34	19	0.00	0.00
Solar Thermal Electric	2005	20	1)	1)	1.00	1.00	3385	2483	32	18	0.00	0.00
Wind Onshore	2005	20	2)	2)	1.00	1.00	1128	790	23	18	0.00	0.00
Wind Offshore	2005	20	2)	2)	1.00	1.00	1975	903	60	34	0.00	0.00
Biomass IGCC	2005	20	0.90	0.90	0.36	0.45	2257	1354	51	46	1.57	1.29
Elec. from Wastes	2005	20	0.90	0.90	0.27	0.37	1918	1241	50	45	0.78	0.63
Geothermal Electricity	2005	20	0.75	0.75	0.39	0.39	4624	3145	254	125	0.31	0.31
Combined heat and power, CHP												
CHP: NGa condensing	2005	35	0.85	0.85	0.54	0.59	570	570	30	28	1.53	1.53
CHP: NGa backpressure	2005	35	0.85	0.85	0.45	0.46	550	500	28	25	1.53	1.53
CHP: Wood condensing	2005	25	0.85	0.85	0.31	0.31	1750	1600	72	72	0.00	0.00
CHP: Wood IGCC	2005	25	0.85	0.85	0.36	0.4	2150	1800	161	90	0.00	0.00
CHP: Coal condensing	2005	35	0.85	0.85	0.42	0.44	1080	1185	53	52	2.56	2.56
CHP: Coal backpressure	2005	35	0.85	0.85	0.36	0.38	1200	1195	56	55	2.56	2.56
CHP: Oil ICE	2005	18	0.85	0.85	0.42	0.42	750	750	35	35	7.50	7.50
CHP: Biogas ICE	2005	15	0.85	0.85	0.39	0.39	2350	2350	115	115	7.50	7.50

TABLE C.2.: *Cost and performance parameters of carbon capture technologies integrated in electricity generation technologies (based on IEA (2004b)).*

Technology	2020	2025	2030	2035	2040	2045	2050
IGCC with CCS (wet cooling)							
Coal carbon content [MtCO2/PJ]	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Fuel efficiency	0.42	0.43	0.44	0.44	0.44	0.45	0.45
Capture efficiency	0.86	0.87	0.87	0.87	0.88	0.88	0.89
Capture cost [M$/MtCO2]	20	20	20	20	20	20	20
Carbon content for sequestration [MtCO2/PJ]	0.20	0.20	0.19	0.19	0.19	0.19	0.19
IGCC with CCS (dry cooling)							
Coal carbon content [MtCO2/PJ]	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Fuel efficiency	0.40	0.41	0.42	0.42	0.42	0.43	0.43
Capture efficiency	0.86	0.87	0.87	0.87	0.88	0.88	0.89
Capture cost [M$/MtCO2]	20	20	20	20	20	20	20
Carbon content for sequestration [MtCO2/PJ]	0.21	0.20	0.20	0.20	0.20	0.20	0.20
Pressurized Coal with CCS							
Coal carbon content [MtCO2/PJ]	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Fuel efficiency	0.39	0.40	0.41	0.41	0.41	0.42	0.42
Capture efficiency	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Capture cost [M$/MtCO2]	20	20	17	17	17	17	17
Carbon content for sequestration [MtCO2/PJ]	0.24	0.23	0.23	0.23	0.22	0.22	0.22
NGCC with CCS							
Gas	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Fuel efficiency	0.53	0.54	0.55	0.55	0.56	0.57	0.57
Capture efficiency	0.86	0.87	0.87	0.87	0.88	0.88	0.89
Capture cost [M$/MtCO2]	29	29	29	29	29	29	29
Carbon content for sequestration [MtCO2/PJ]	0.09	0.09	0.09	0.09	0.09	0.09	0.09